University of Colorado Boulder

ASEN 4018 Senior Projects, Fall 2018
Conceptual Design Review (CDR)

CCAR

VANTAGE

Visual **A**pproximation of **N**anosat **T**rajectories to **A**ugment **G**round-based **E**stimation

Team: *Aaron Aboaf, Dylan Bossie, Sean Downs, Justin Fay, Marshall Herr, Josh Kirby, Lara Lufkin, Richard Moon, Nicholas Renninger, Zach Talpas, Jerry Wang*

Customer: *Prof. Penina Axelrad (CCAR), John Gaebler (CCAR)*

Advisor: *Prof. Marcus Holzinger*

Presenters

Project Purpose and Objectives	Lara Lufkin
Design Solution	Marshall Herr
Critical Project Elements	Aaron Aboaf
Design Requirements and their Satisfaction	Aaron Aboaf, Josh Kirby, Dylan Bossie, Richard Moon, Jerry Wang
Project Risks	Nick Renninger
Verification and Validation	Zach Talpas, Aaron Aboaf
Project Planning	Nick Renninger

Project Purpose and Objectives

Motivation

Project Objectives

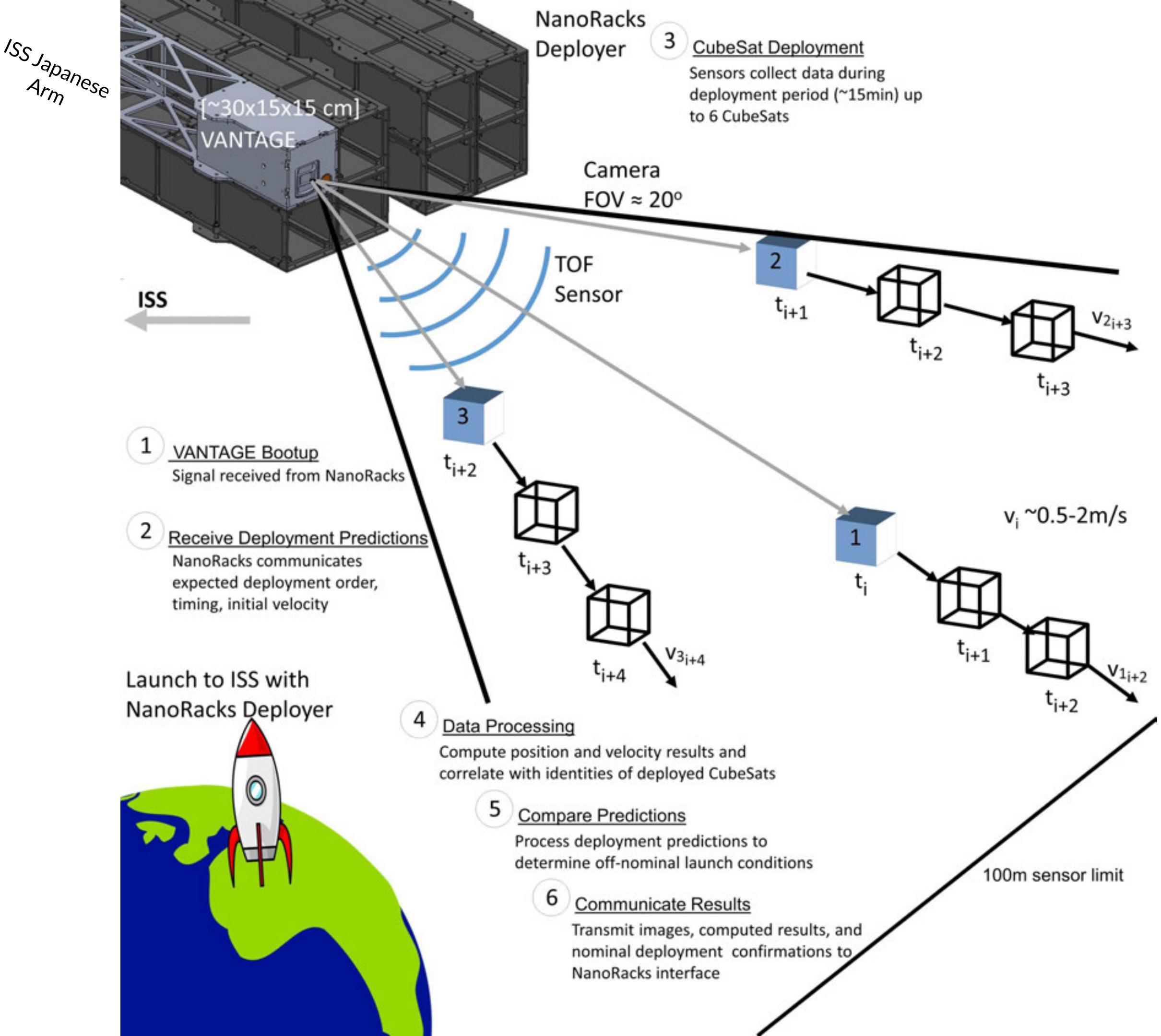
Objectives:

The **long term vision** of this project is to augment existing, ground-based CubeSat Space Situational Awareness (SSA) by observing CubeSat deployments from the perspective of the space-based deployer.

This year's VANTAGE team will produce a **proof of concept** for this mission by developing a **ground based prototype** which will be tested using a simulated CubeSat deployment in a laboratory environment.

Project Stakeholders:

- Customer: Prof. Axelrad and John Gaebler
- Associated Company: NanoRacks


ISS Japanese Arm
NanoRacks Deployer
[~30x15x15 cm]
VANTAGE
3 CubeSat Deployment
Sensors collect data during deployment period (~15min) up to 6 CubeSats
Camera FOV ≈ 20°
TOF Sensor
ISS
2
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t_{i+3}
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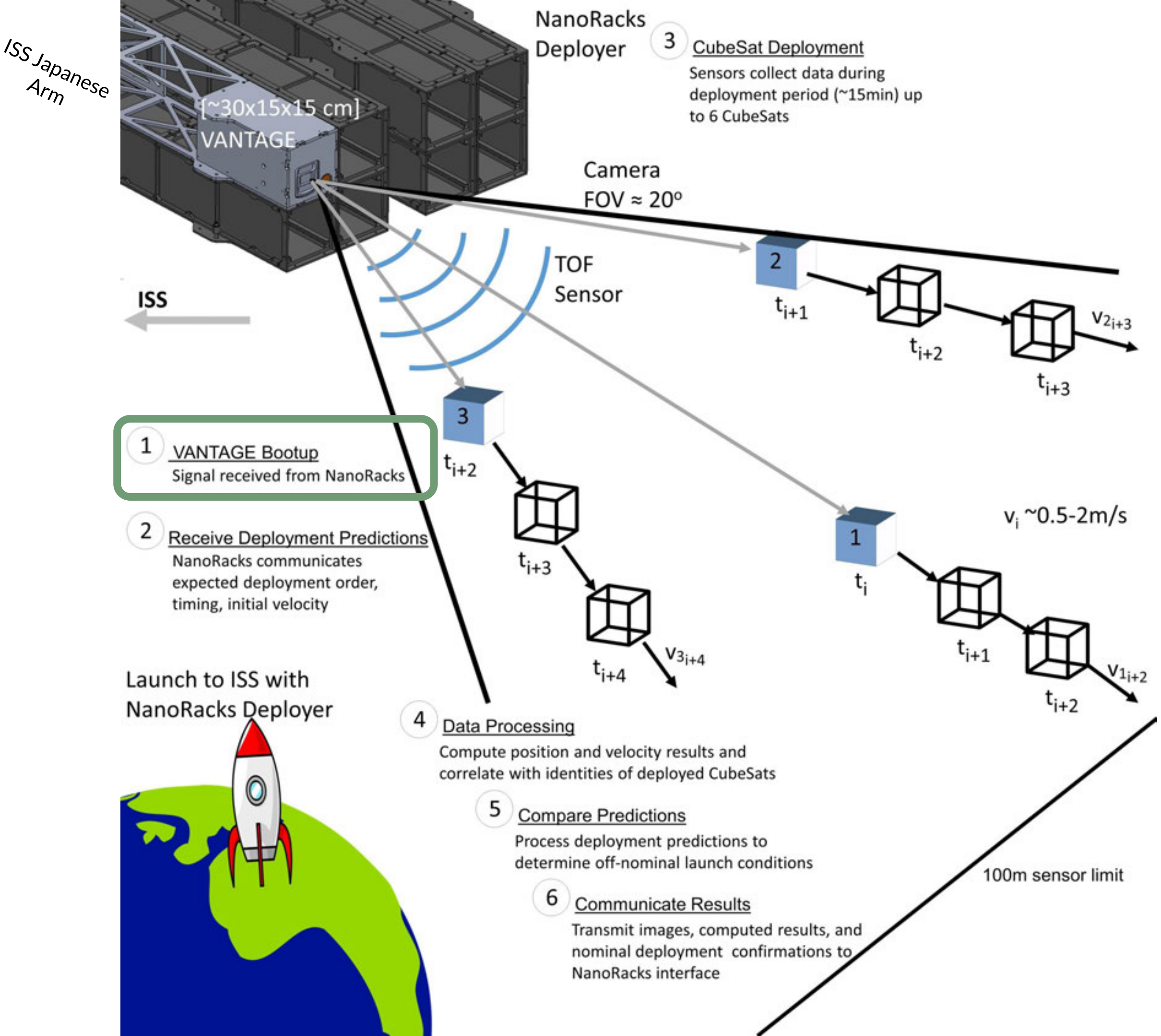
1 VANTAGE Bootup
Signal received from NanoRacks
2 Receive Deployment Predictions
NanoRacks communicates expected deployment order, timing, initial velocity
Launch to ISS with NanoRacks Deployer
4 Data Processing
Compute position and velocity results and correlate with identities of deployed CubeSats
5 Compare Predictions
Process deployment predictions to determine off-nominal launch conditions
6 Communicate Results
Transmit images, computed results, and nominal deployment confirmations to NanoRacks interface
100m sensor limit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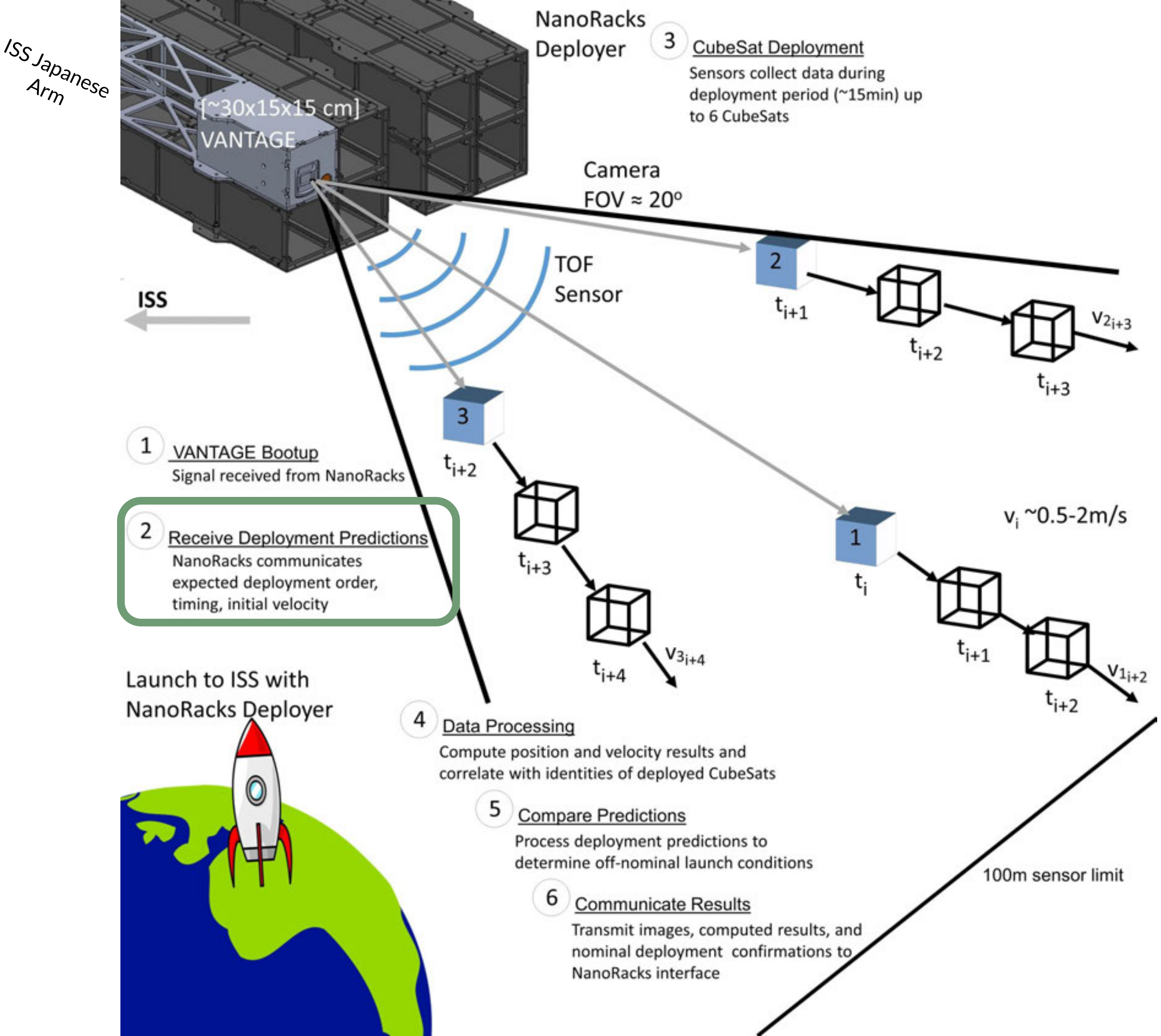
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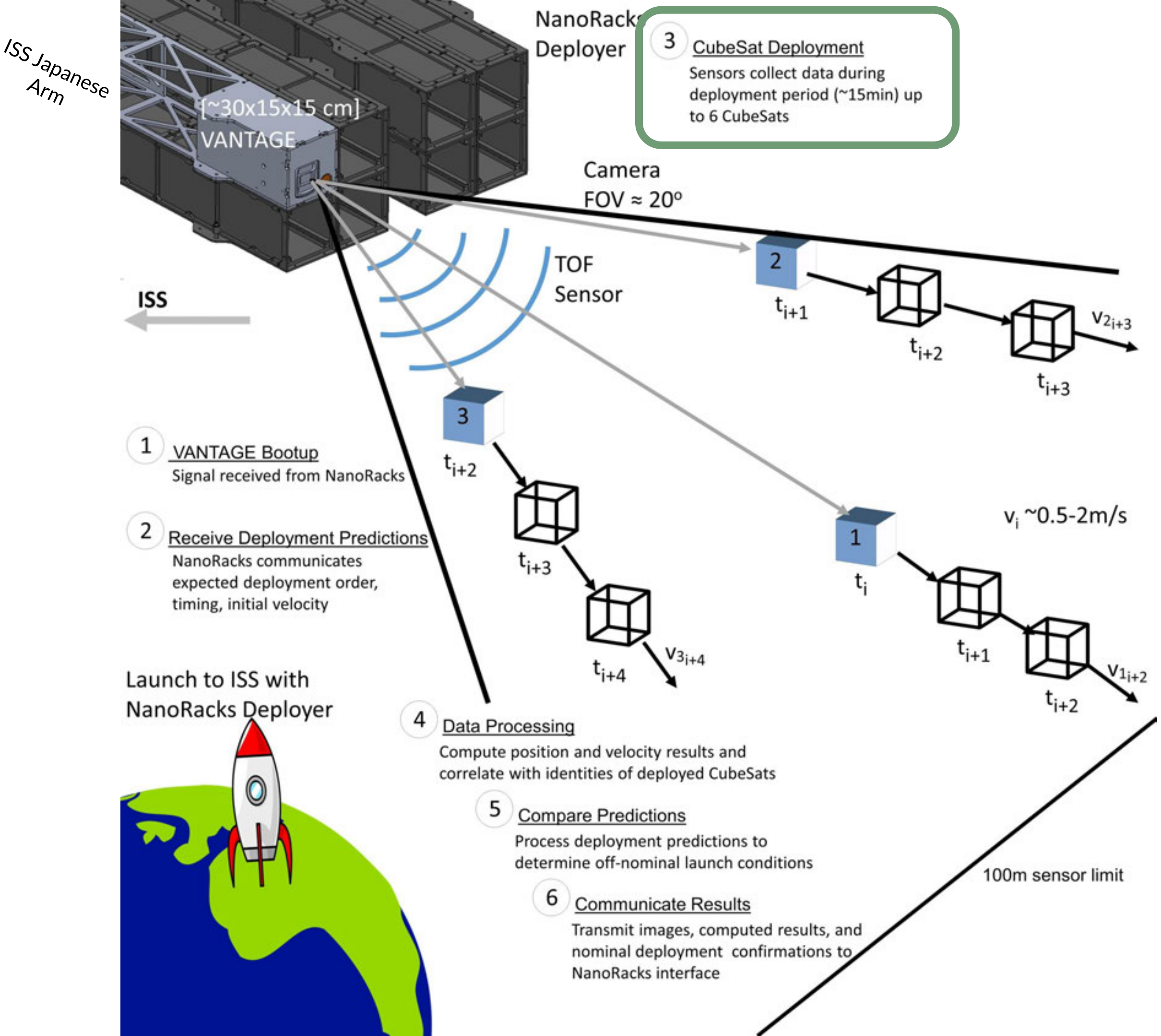

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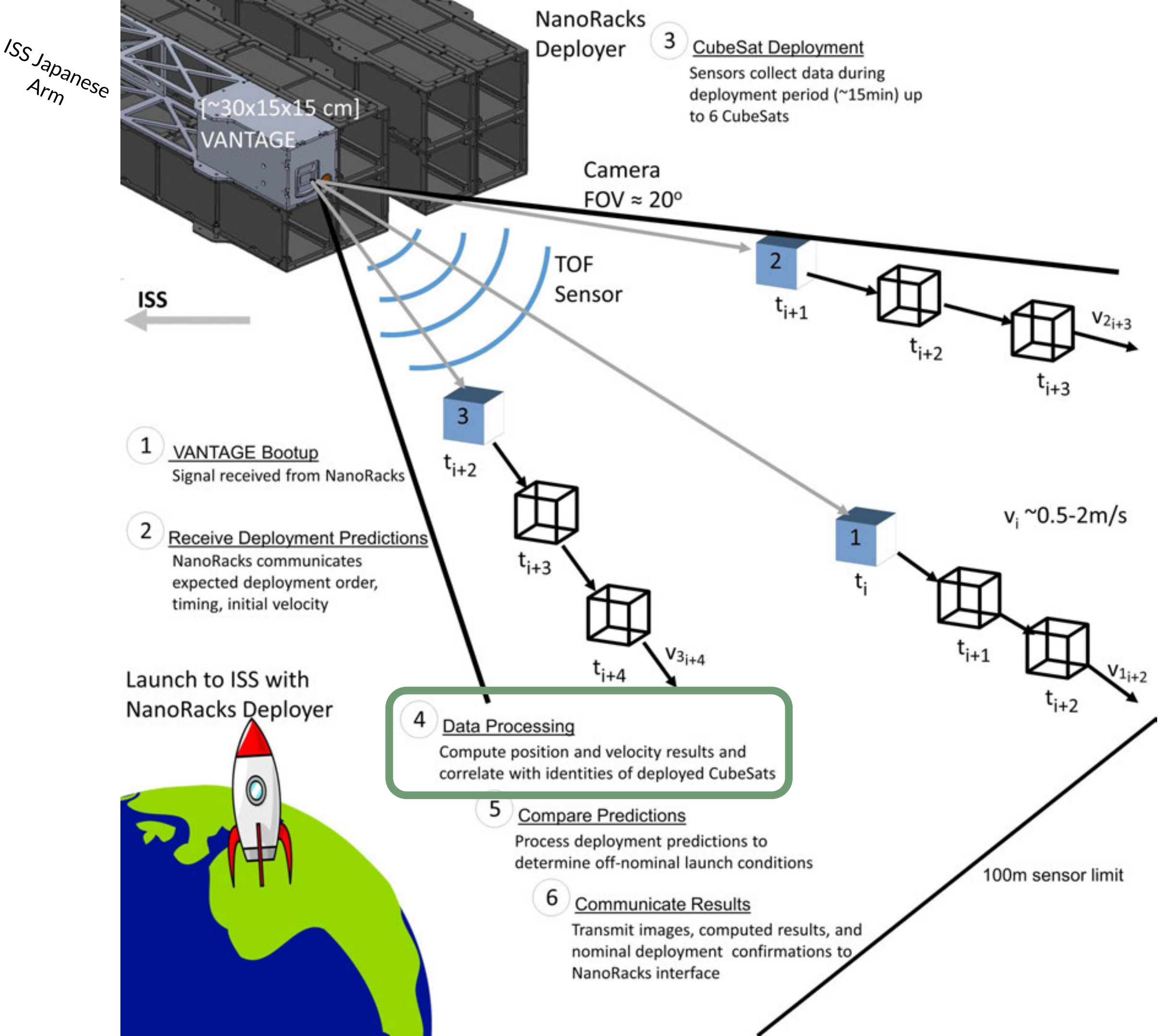
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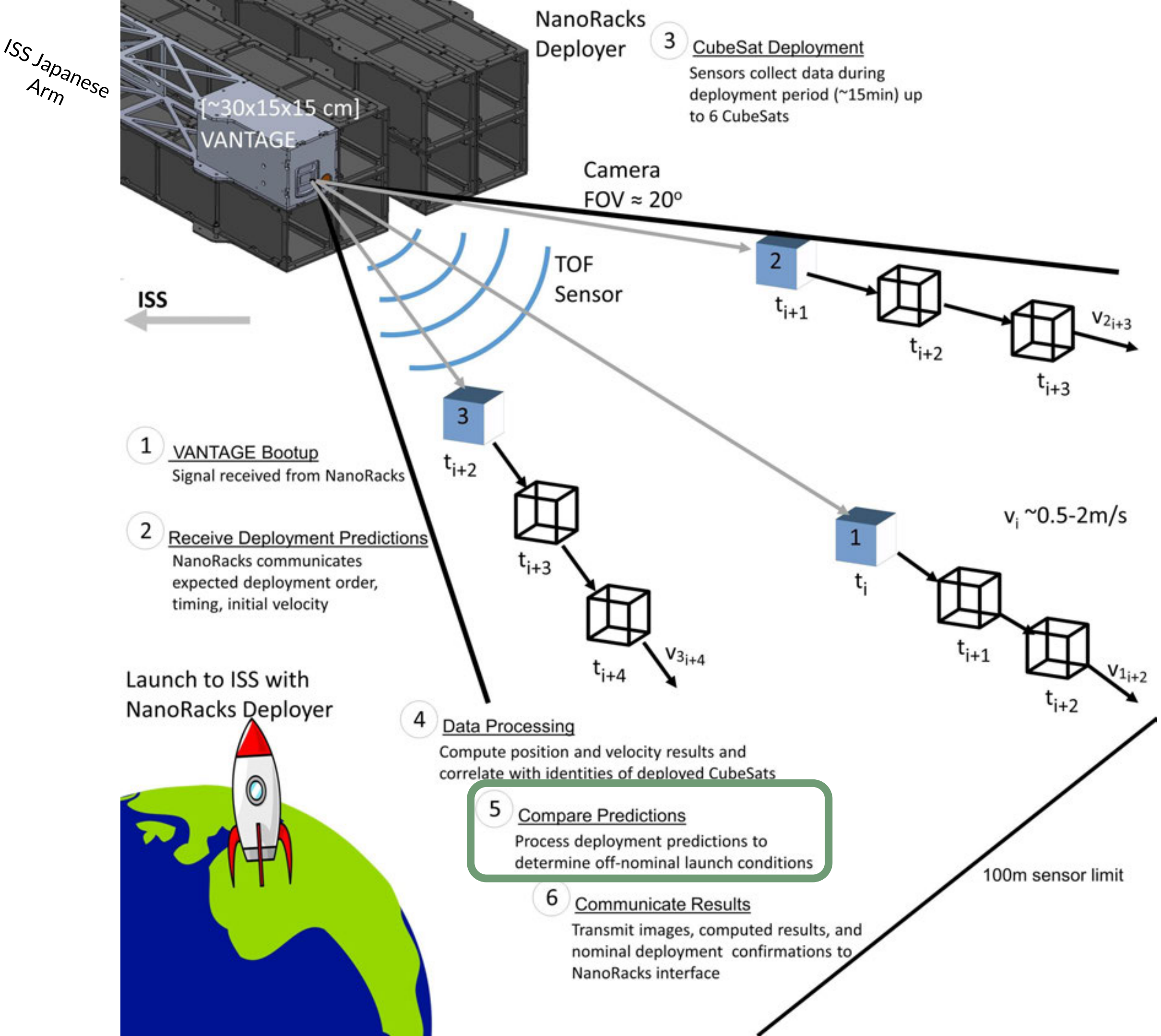
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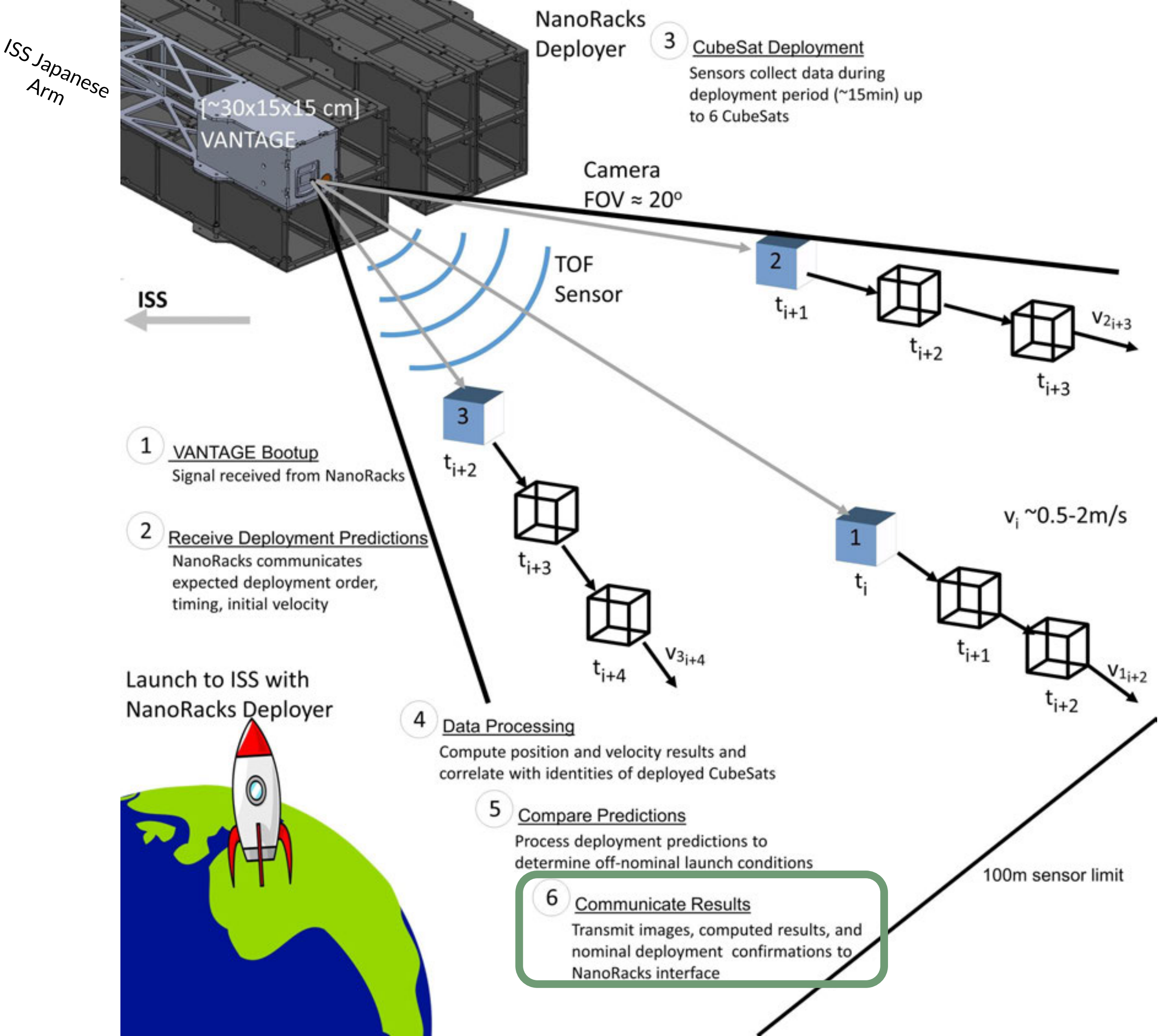

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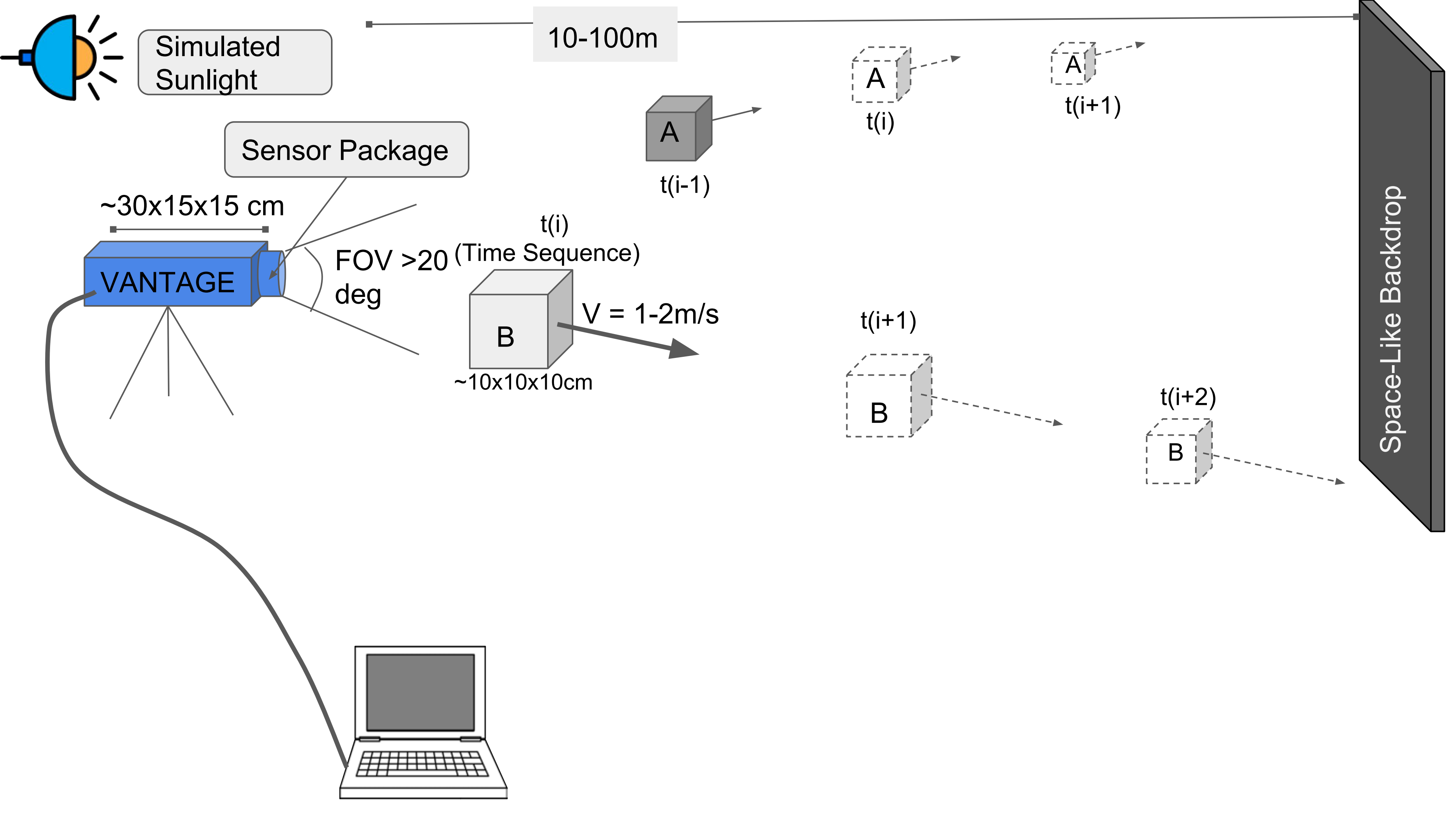
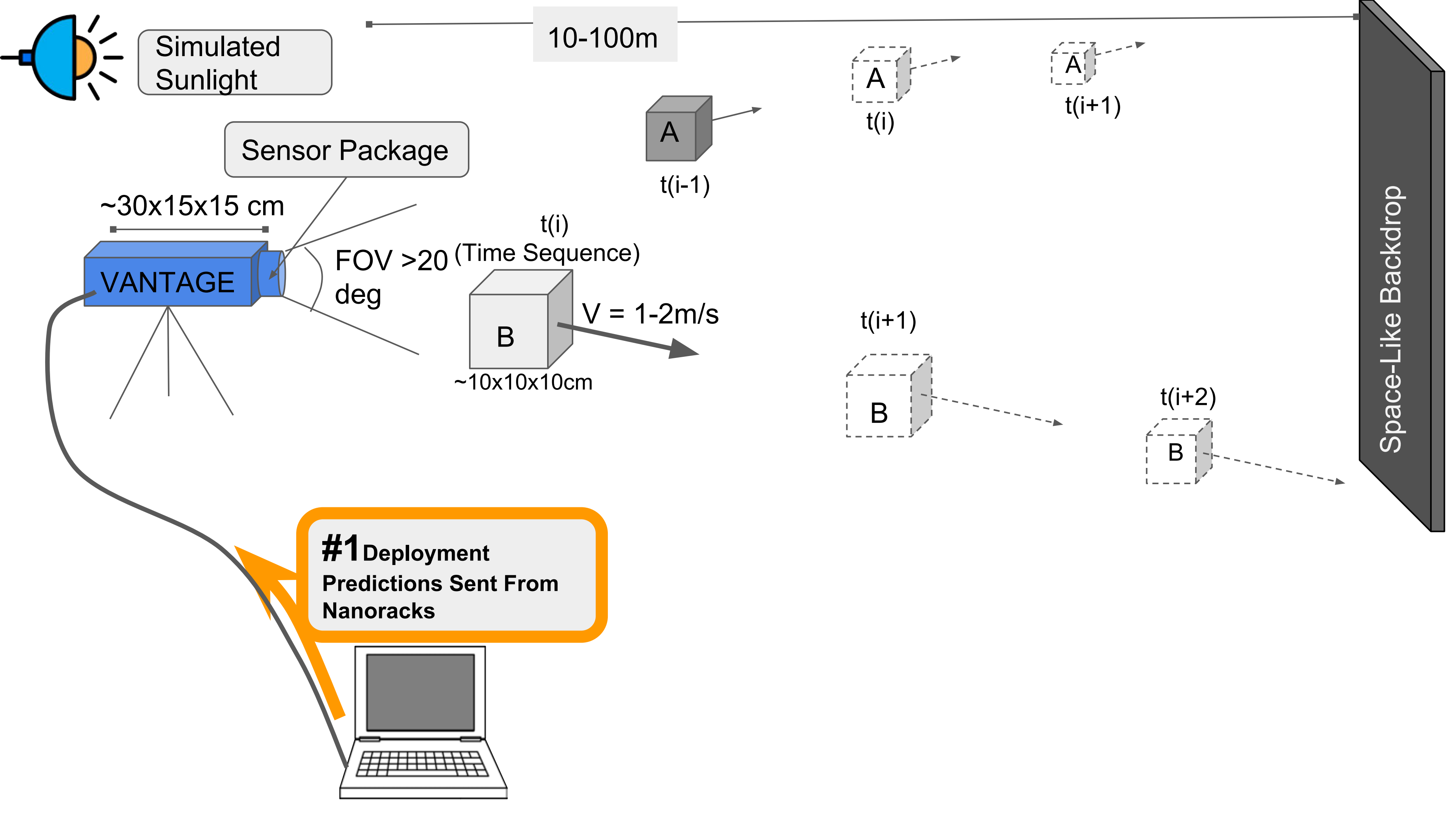


Simulated Sunlight
10-100m
Sensor Package
~30x15x15 cm
VANTAGE
FOV >20 deg
t(i) (Time Sequence)
A
t(i-1)
A
t(i)
A
t(i+1)
B
~10x10x10cm
V = 1-2m/s
t(i+1)
B
t(i+2)
B
Space-Like Backdrop



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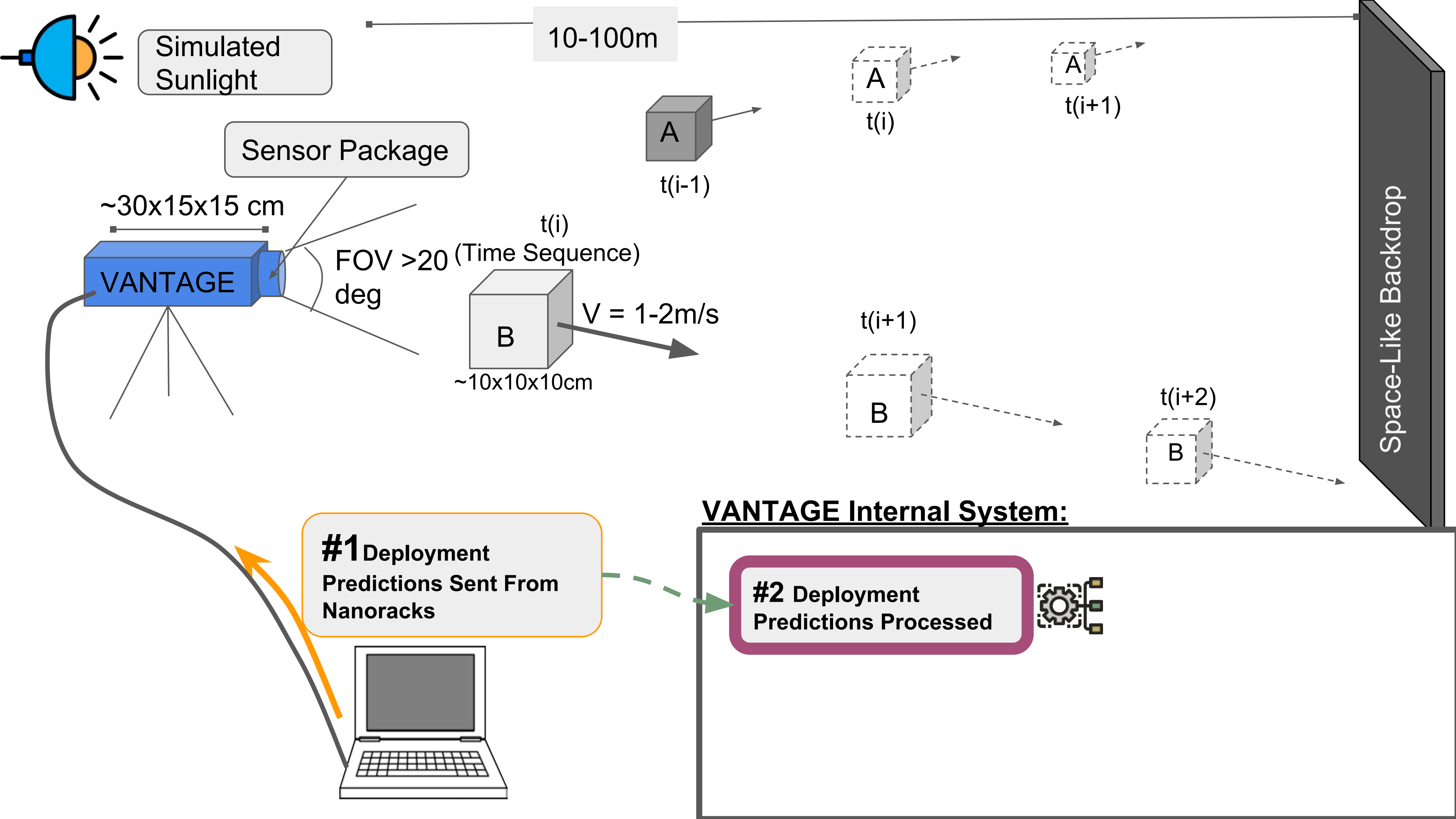

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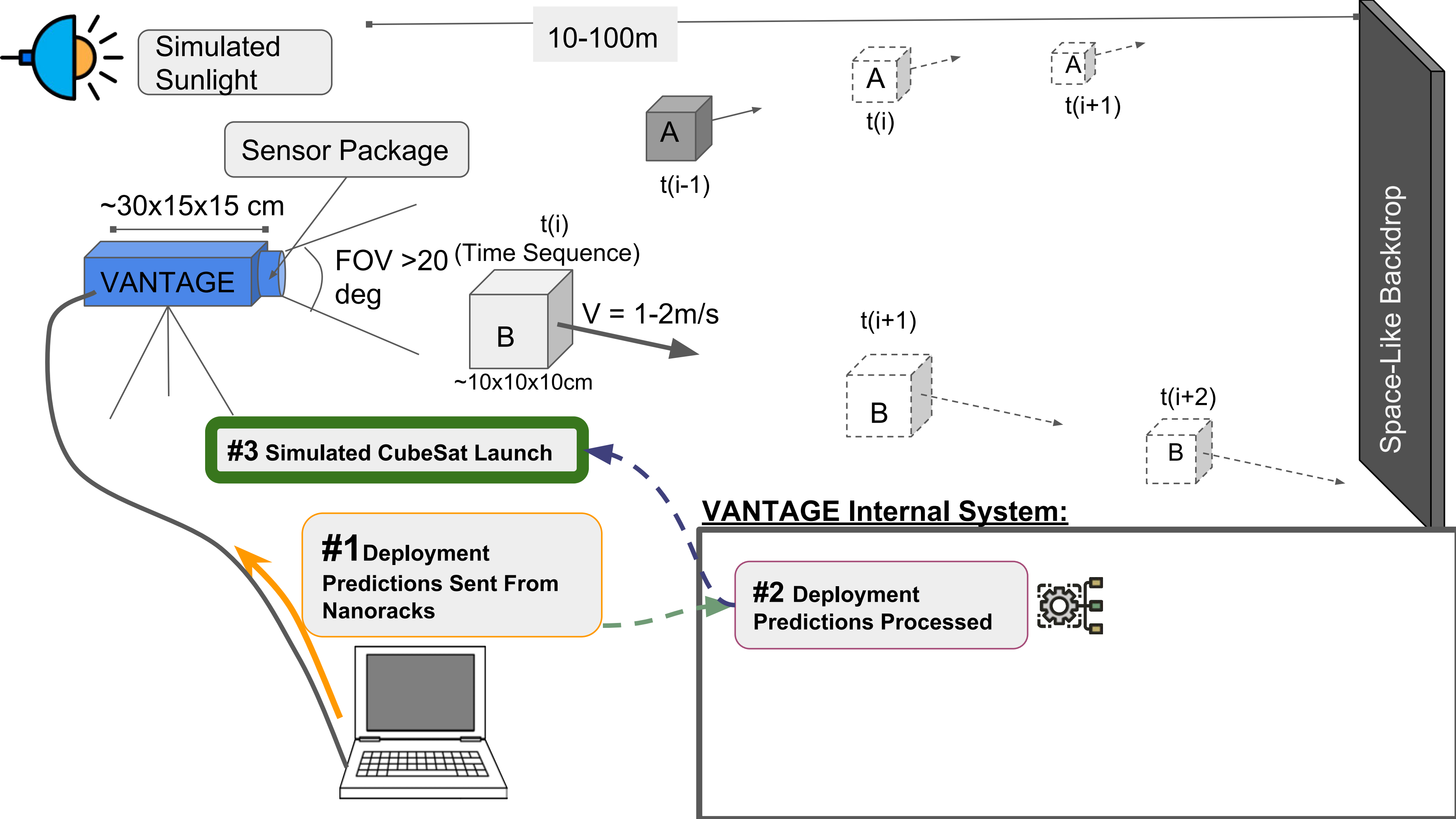
Space-Like Backdrop
VANTAGE Internal System:
#1 Deployment Predictions Sent From Nanoracks
#2 Deployment Predictions Processed



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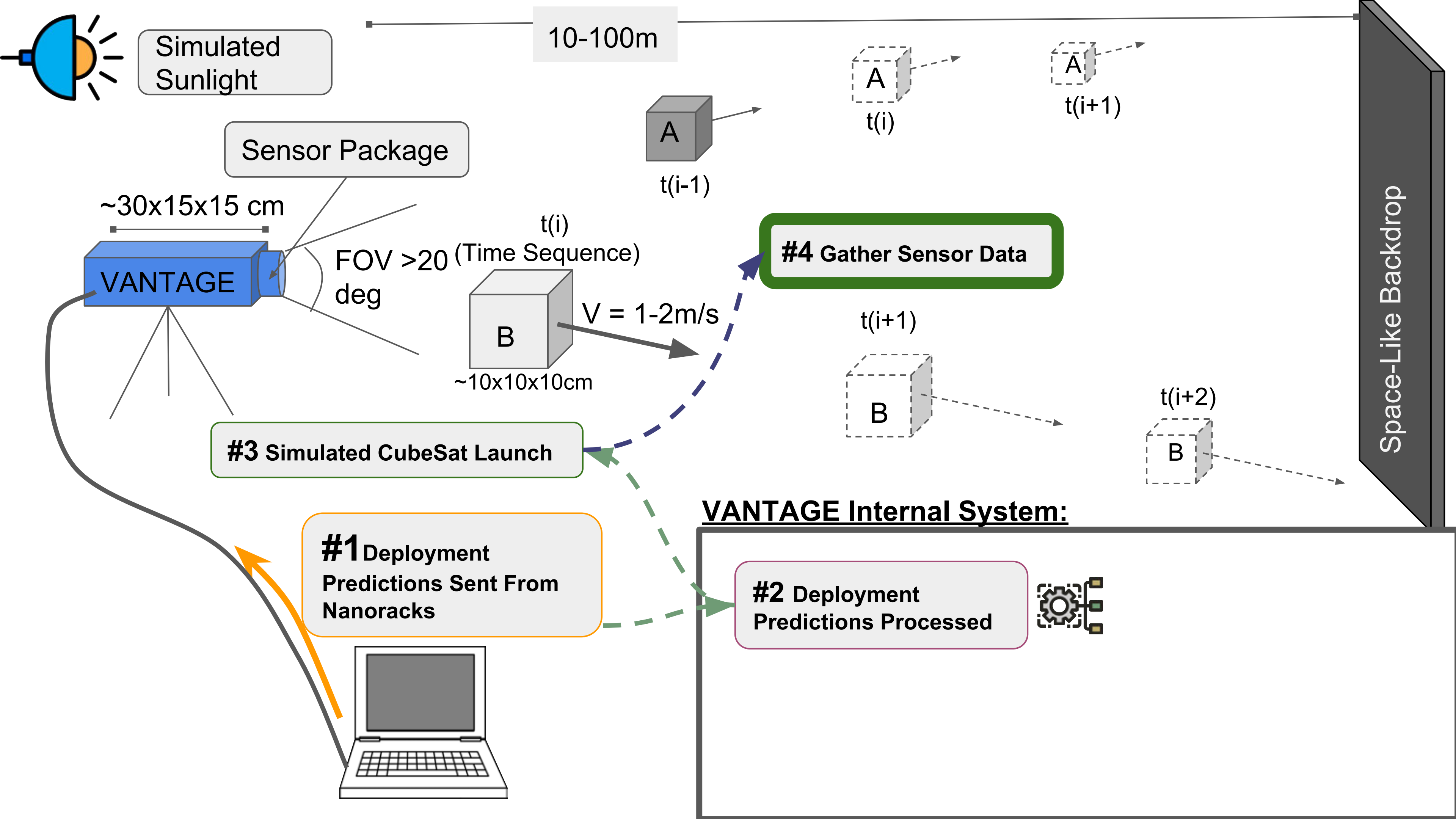
Space-Like Backdrop
#3 Simulated CubeSat Launch
VANTAGE Internal System:
#1 Deployment Predictions Sent From Nanoracks
#2 Deployment Predictions Processed



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#4 Gather Sensor Data
t(i+1)
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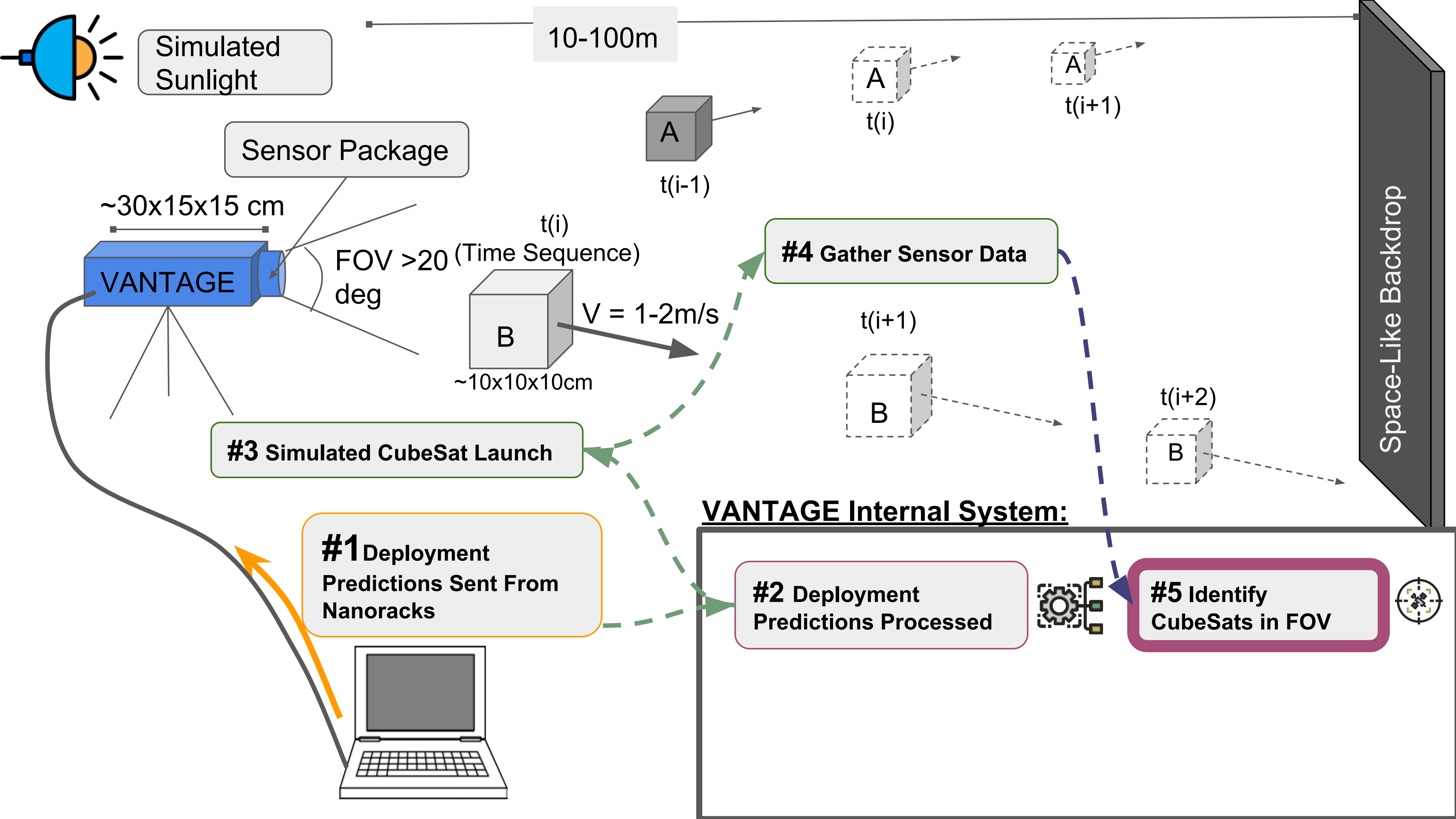

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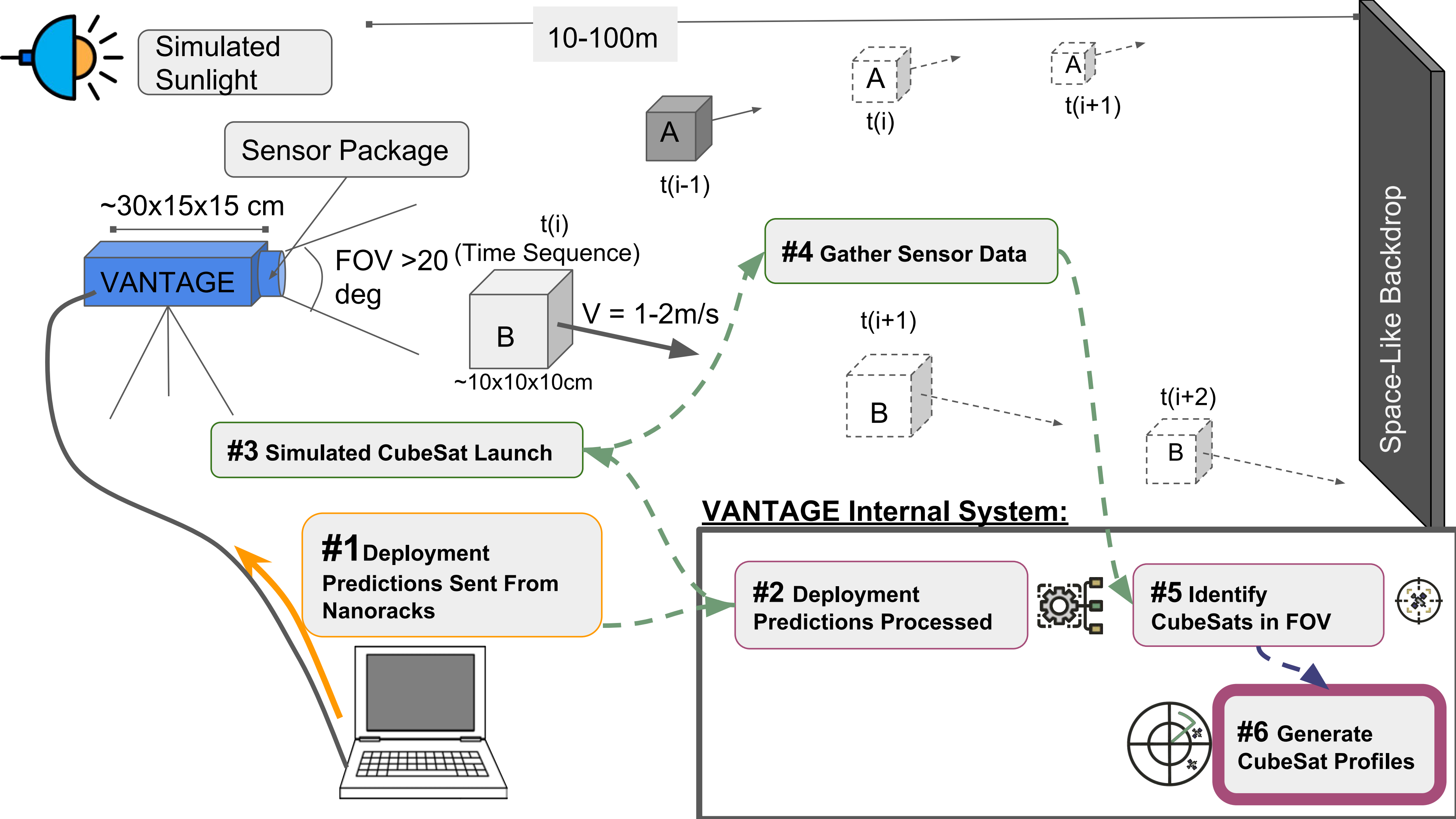
#3 Simulated CubeSat Launch
VANTAGE Internal System:
#1 Deployment Predictions Sent From Nanoracks
#2 Deployment Predictions Processed
#5 Identify CubeSats in FOV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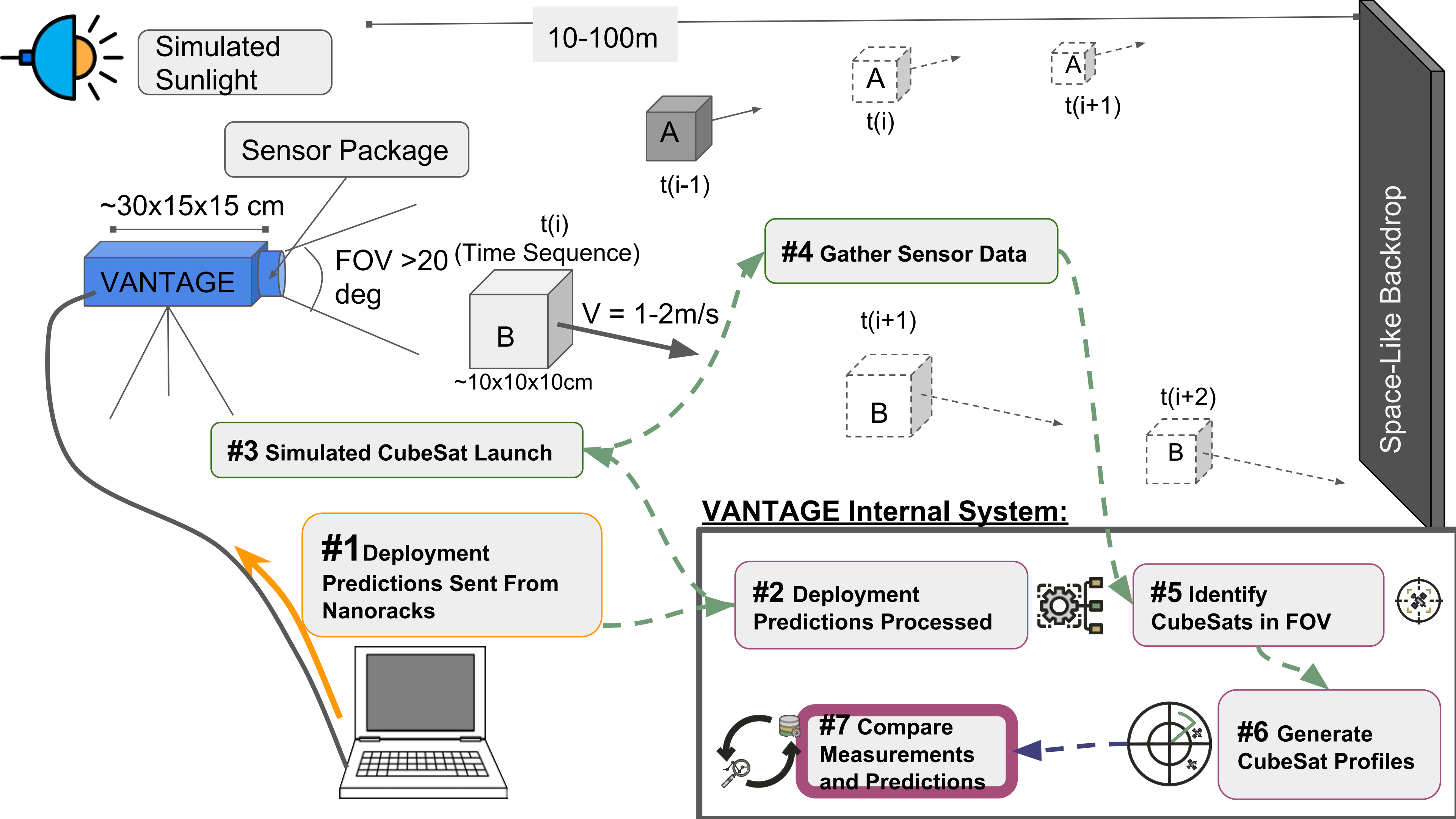
#1 Deployment Predictions Sent From Nanoracks
VANTAGE Internal System:
#2 Deployment Predictions Processed
#5 Identify CubeSats in FOV
#6 Generate CubeSat Profiles



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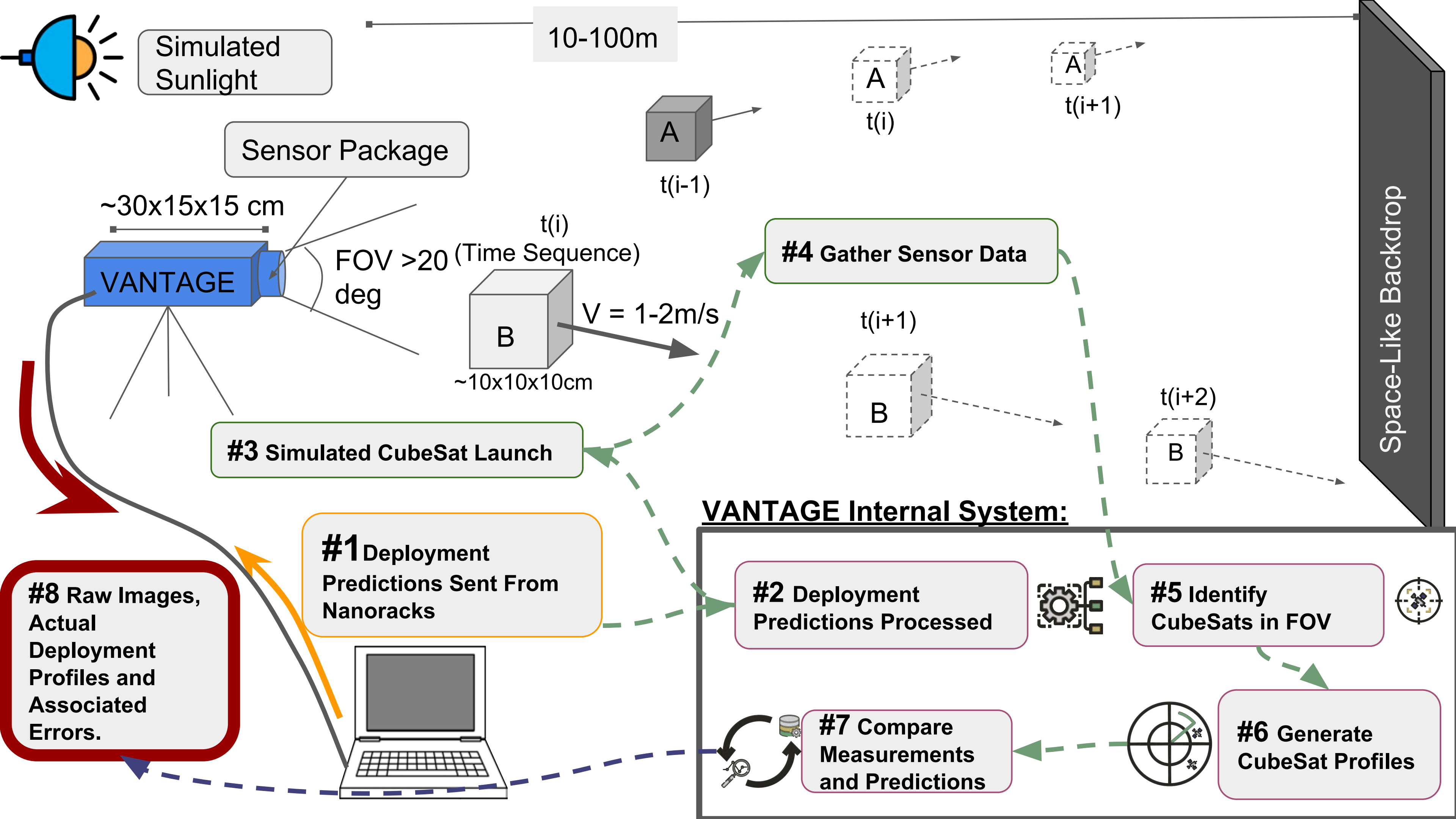
#6 Generate CubeSat Profiles
#7 Compare Measurements and Predictions



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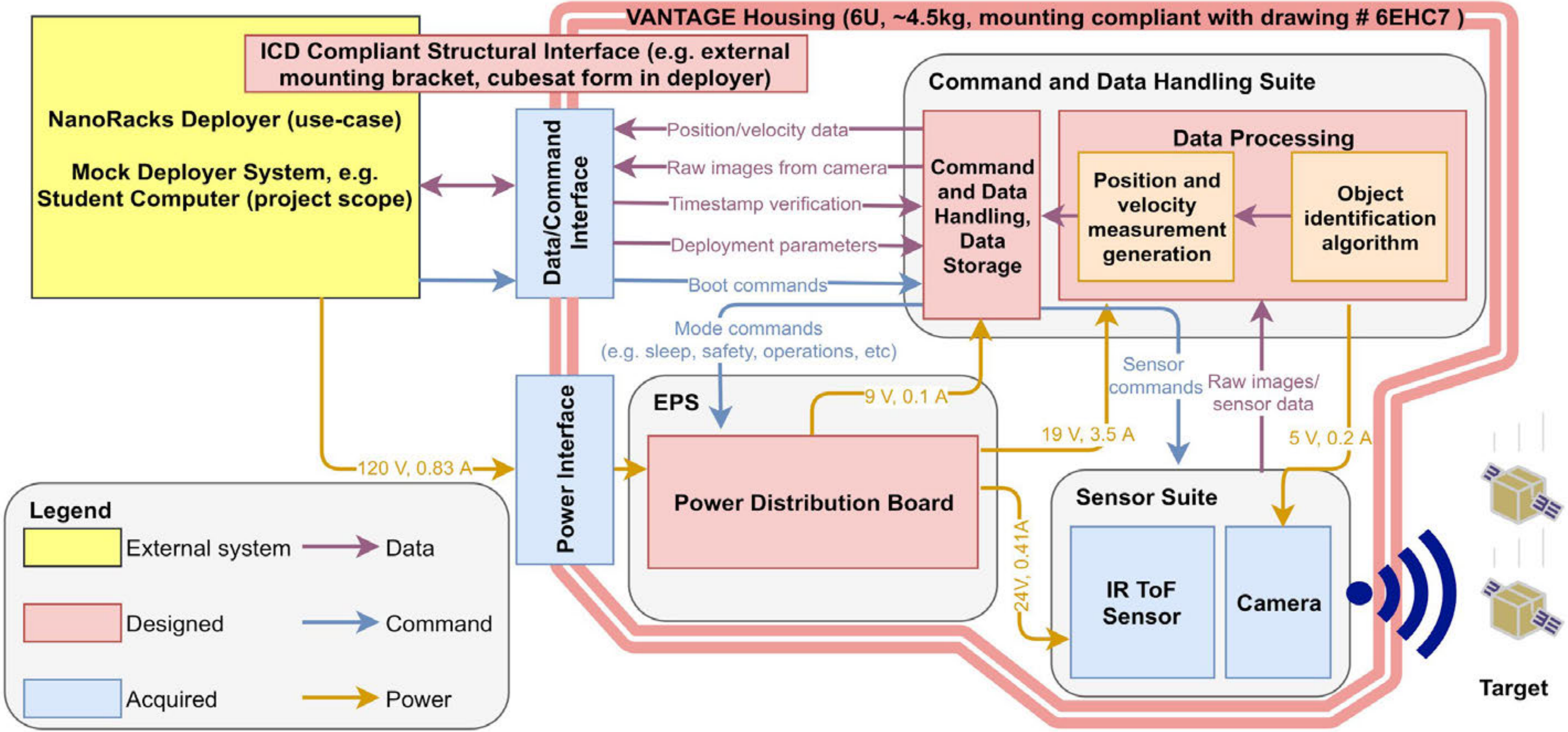
VANTAGE Internal System:
#1 Deployment Predictions Sent From Nanoracks
#2 Deployment Predictions Processed
#5 Identify CubeSats in FOV
#8 Raw Images, Actual Deployment Profiles and Associated Errors.
#7 Compare Measurements and Predictions
#6 Generate CubeSat Profiles

Functional Requirements

Req.	Description
FR.1	The system shall support in-focus imaging of at most 6 mock 1U CubeSats at some range between 3 and 100 meters from the VANTAGE payload.
FR.2	The system shall receive and interpret commands and the deployment manifest from a PC which simulates the NanoRacks use-case system.
FR.3	The system shall accept power analogous to that which is available from the NanoRacks use-case system.
FR.4	The system shall integrate mechanically with a structural interface which simulates the NanoRacks use-case system.
FR.5	The system shall uniquely detect and track up to 6 mock 1U-3U CubeSats while they remain between 3 and 100 m of the VANTAGE payload.
FR.6	The system shall estimate the position and velocity vectors of CubeSats between a distance of 3 and 100 m.
FR.7	The system shall recognize off-nominal deployment cases, which shall include off-nominal relative initial velocities and off-nominal deployment times from the test system.
FR.8	The system shall report position/velocity vector measurements, off-nominal deployment cases, and raw images from the current mock deployment to the PC which simulates the NanoRacks use-case system before the next NanoRacks CubeSat Deployer (NRCSD) tube deployment would normally occur in the use-case.

Design Solution

Functional Block Diagram



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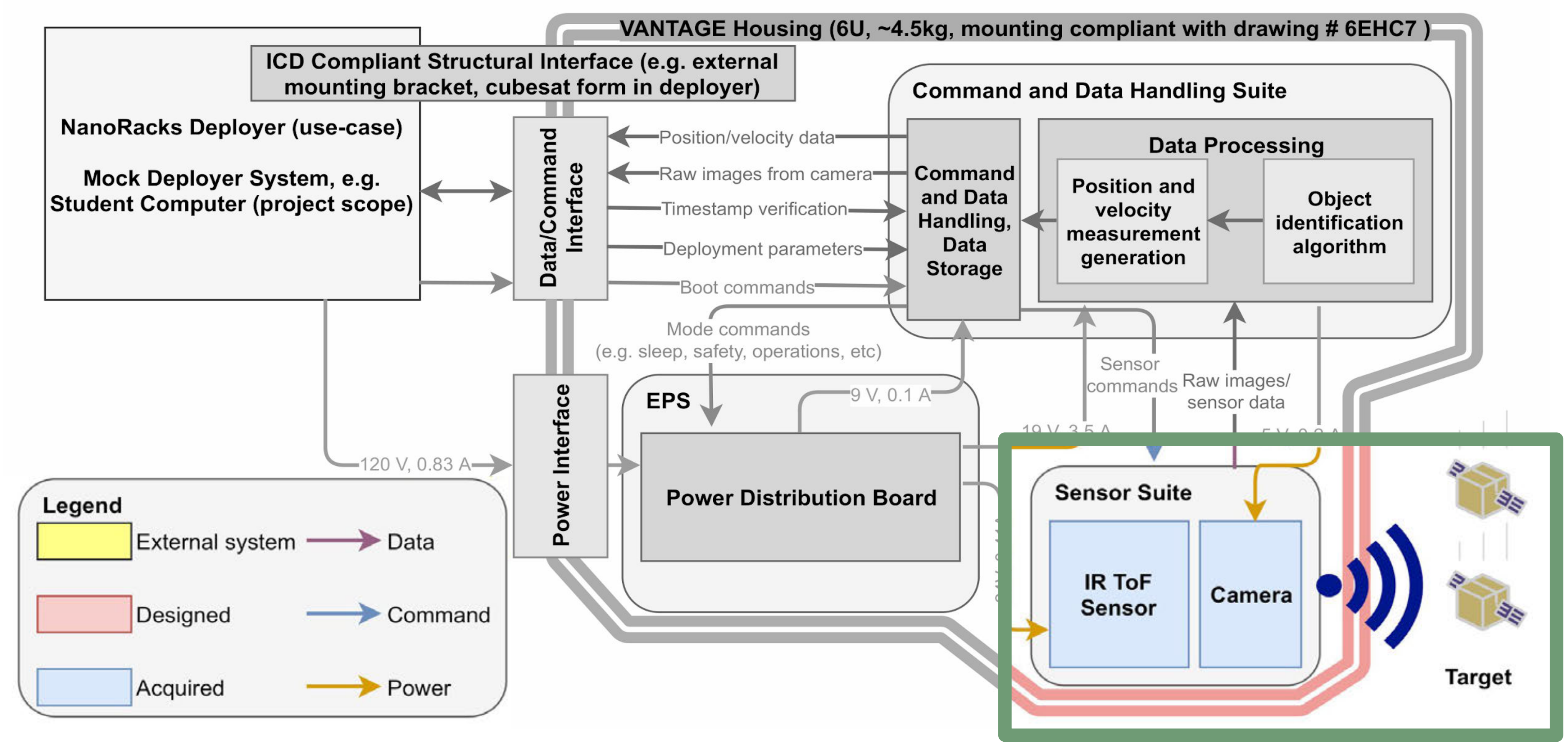

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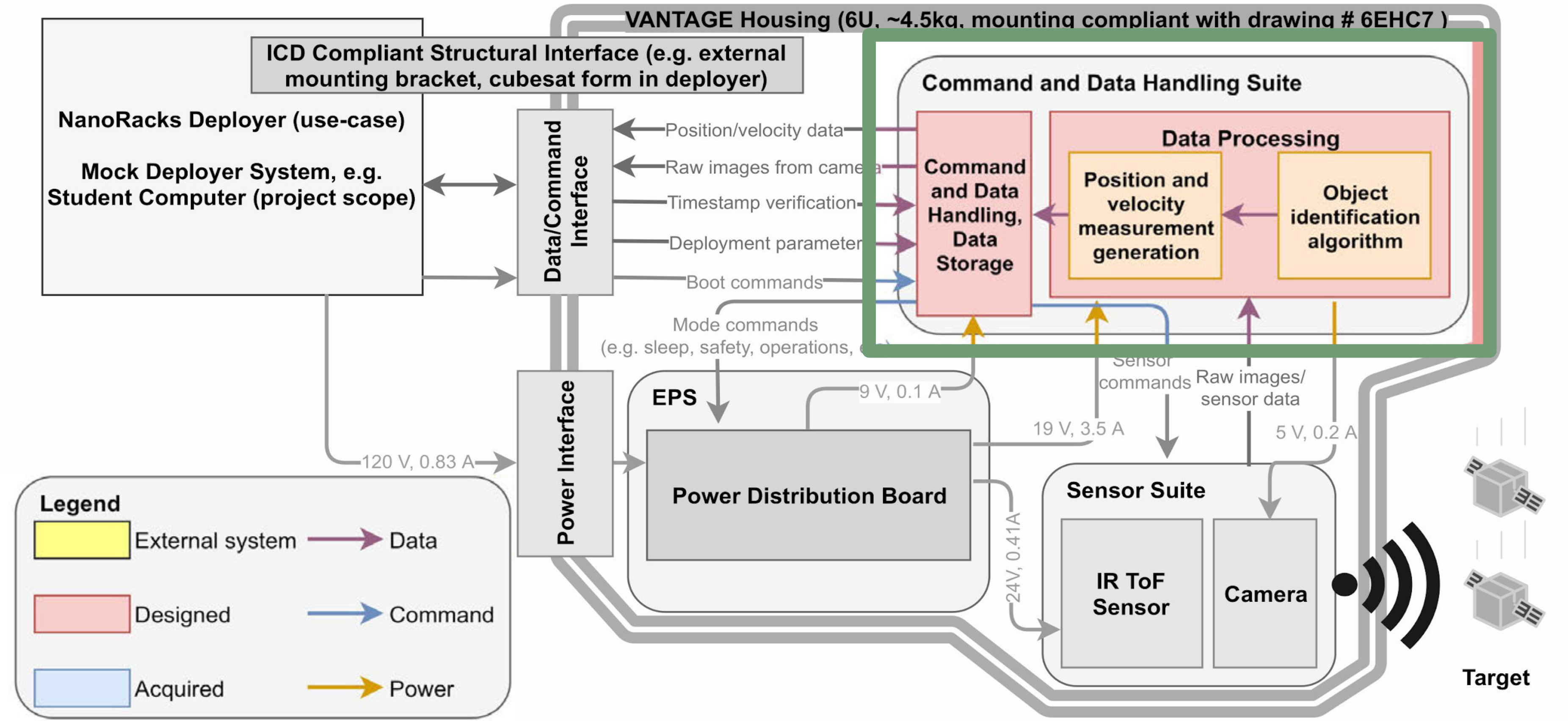

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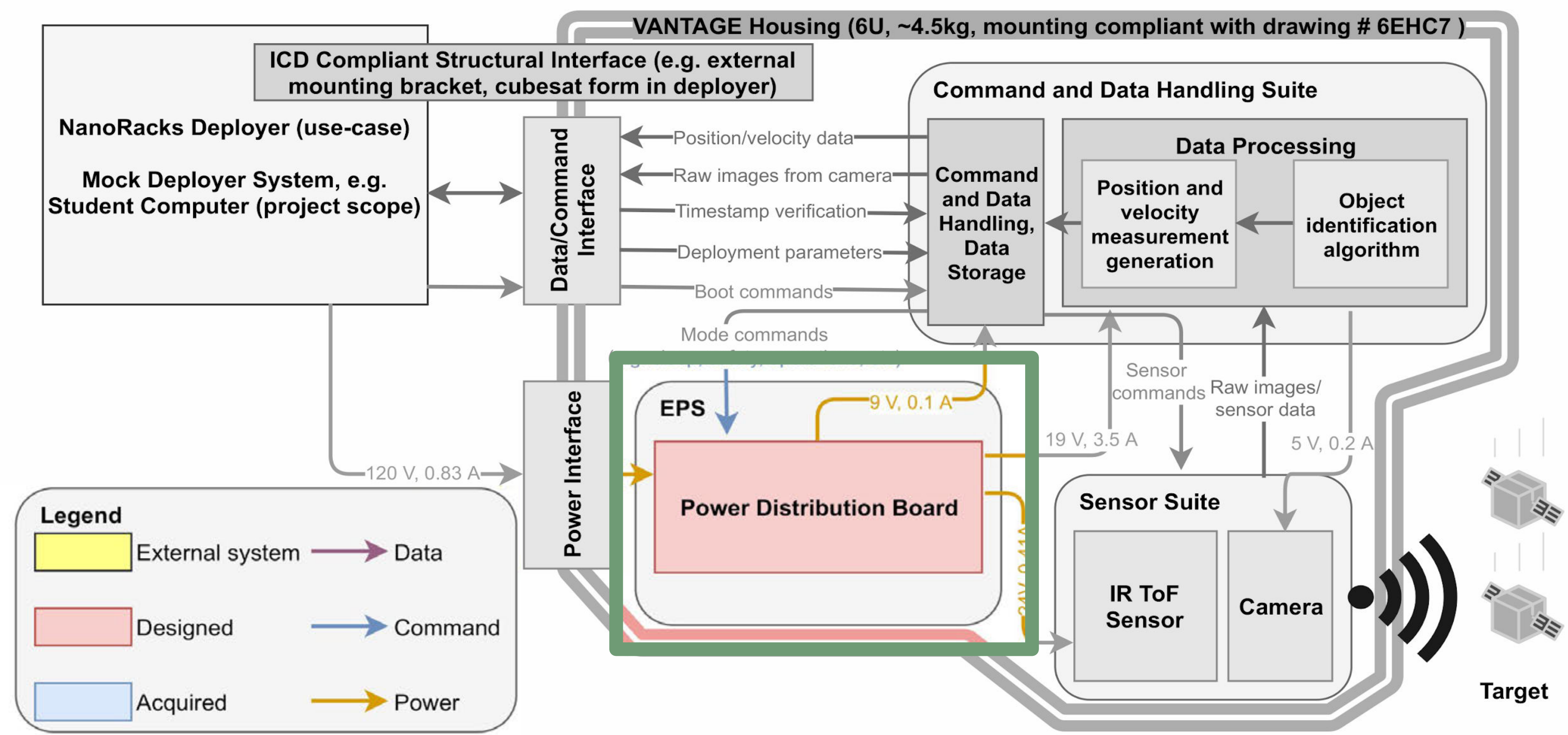

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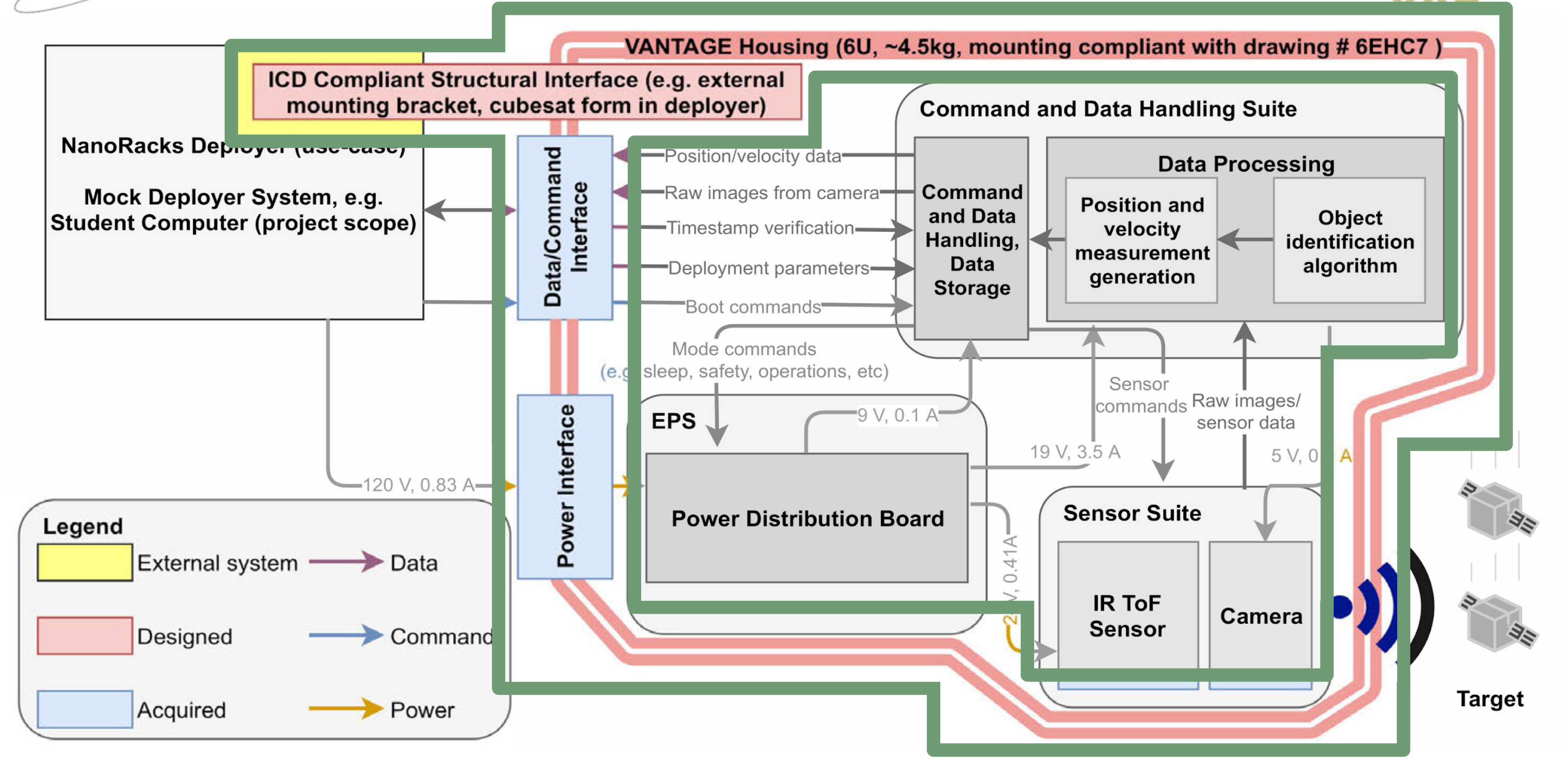

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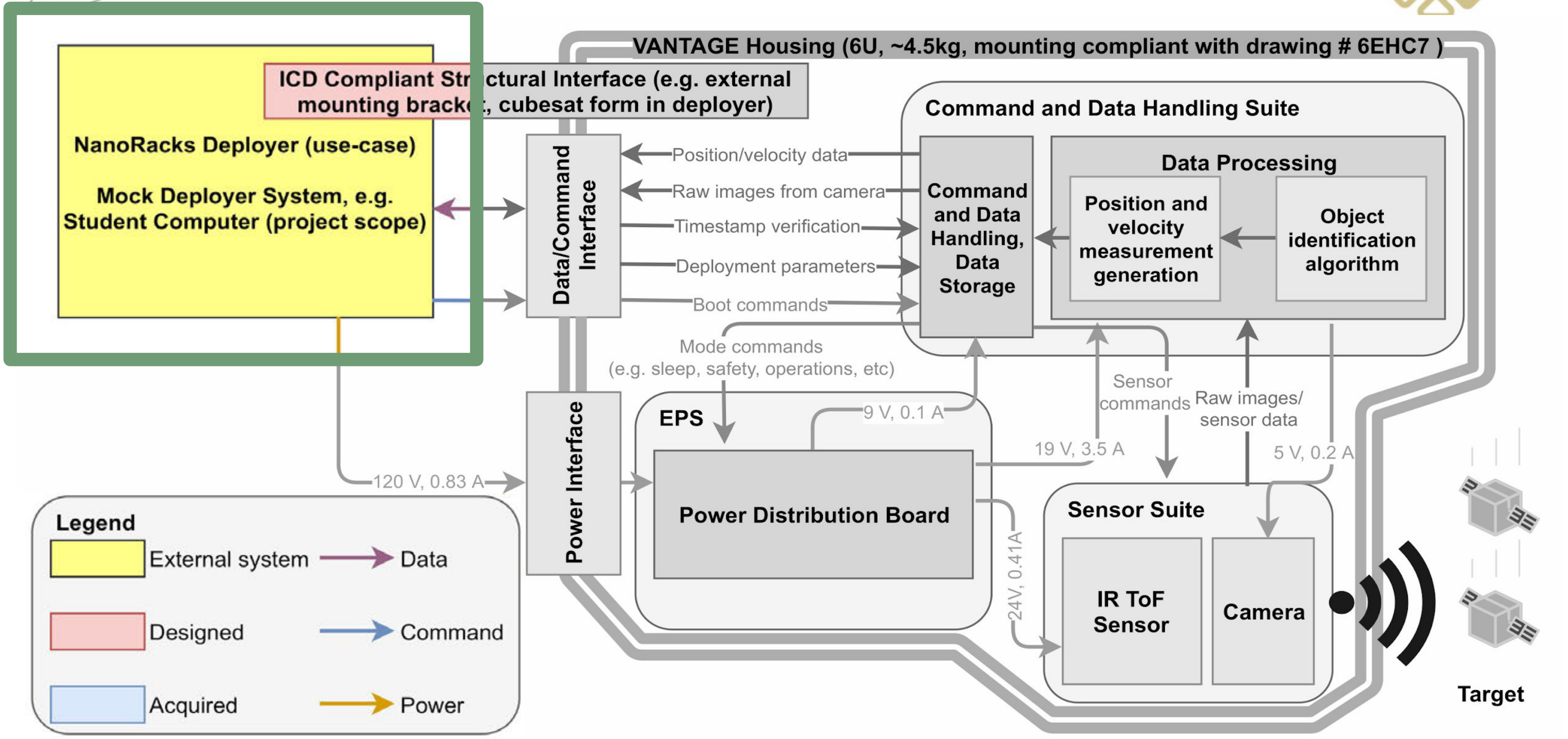
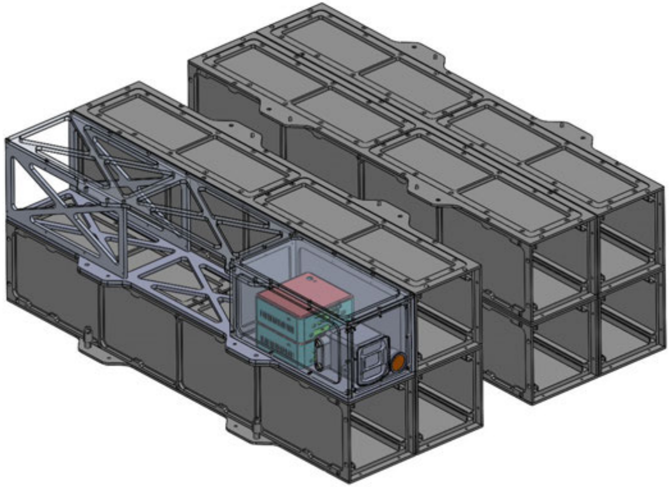
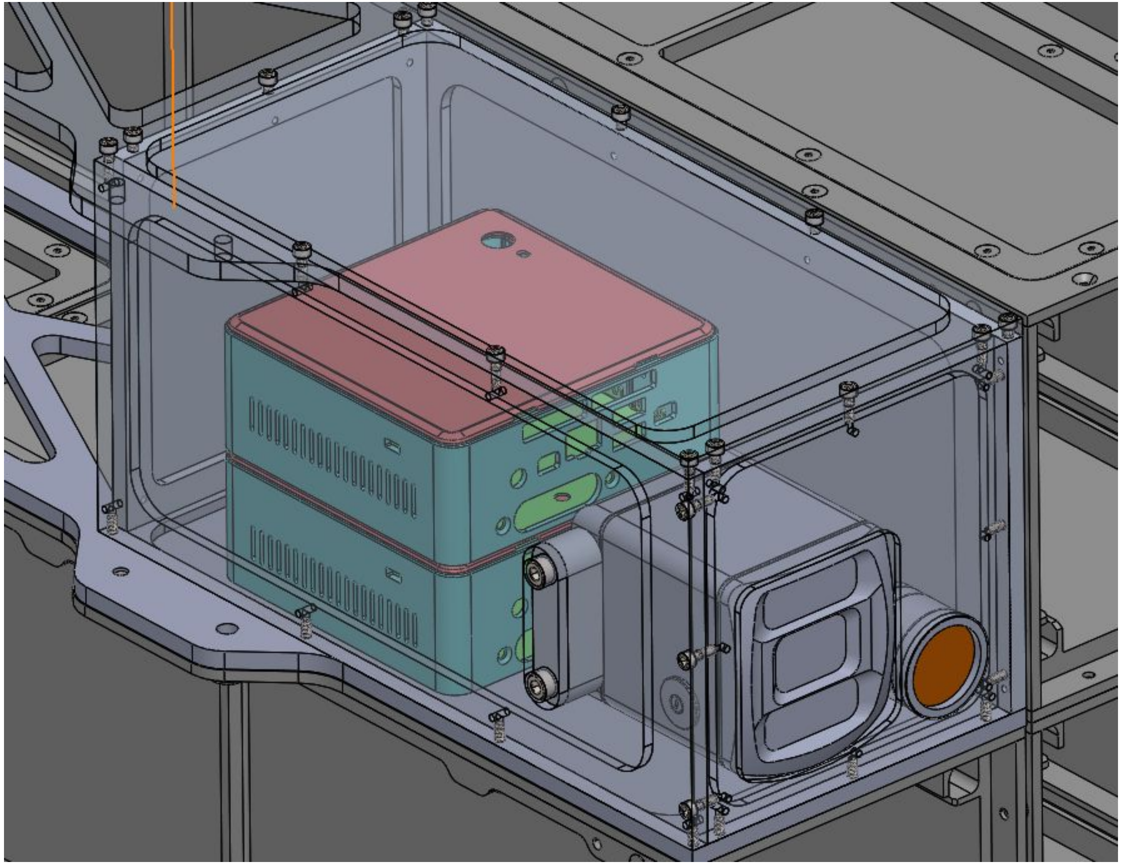


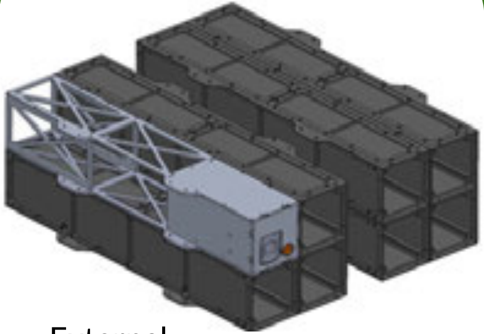
VANTAGE Overview





Baseline Design Overview

Interface With NanoRacks Ground-based Hardware



External Mounting

Avionics and Software

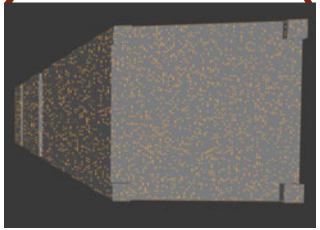
Next Unit of Computing (NUC)

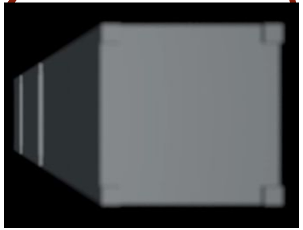
MATLAB SW

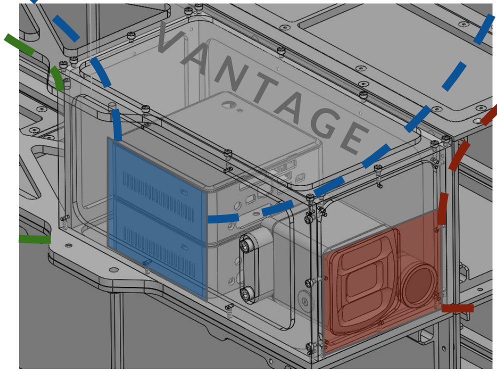
Acquire Data

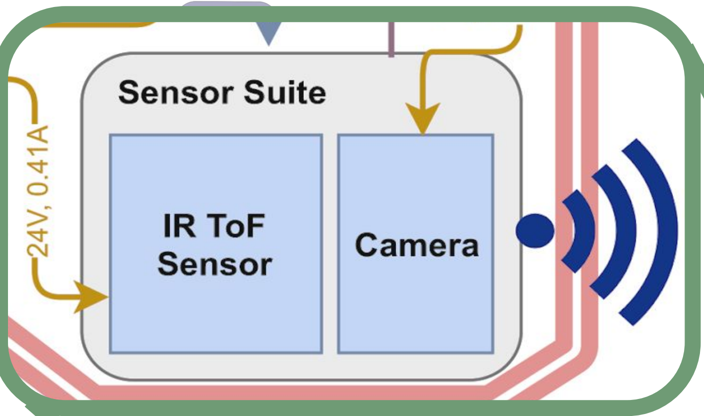
Time of Flight (TOF) Camera

Monochrome Camera

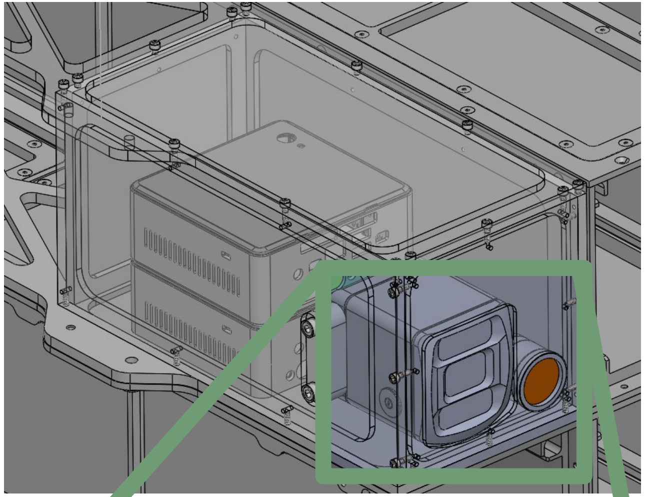


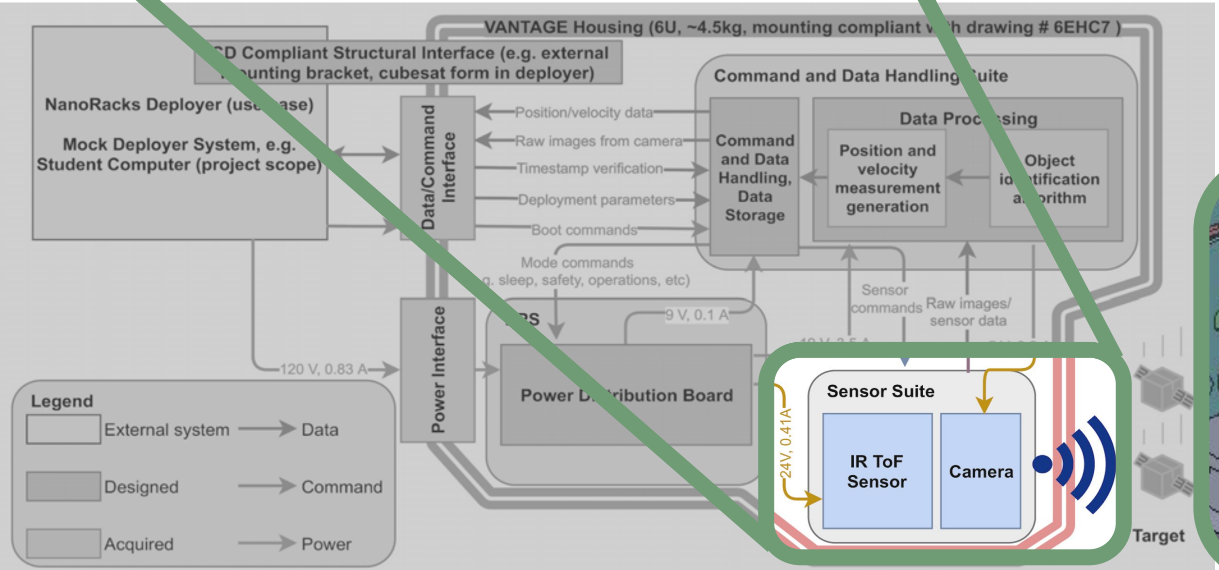


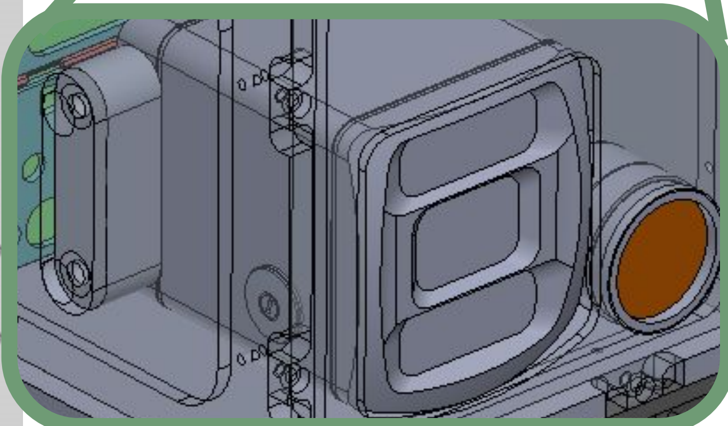




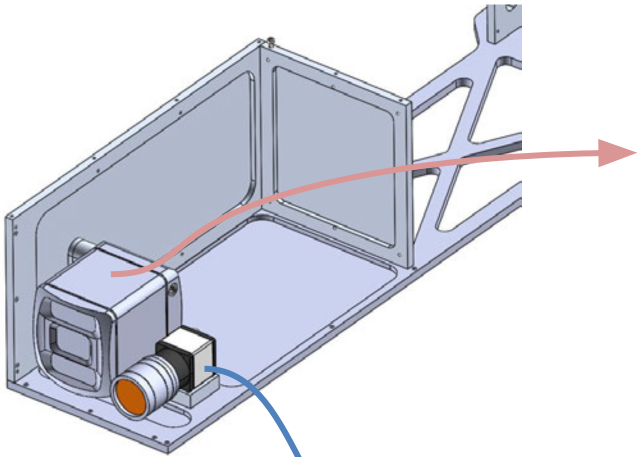
Sensor Design Solution







Sensor Design Solution



IFM O3D313 IR Time of Flight (ToF) Camera

Early Centroid Determination

Description	Requirement	ToF Camera
Position Accuracy	10 cm	2 cm
Inferred Velocity Accuracy*	1 cm/s	0.1 cm/s

*Velocity inference model in backup

EO-6412 Monochrome CMOS Camera

Cross-Range Tracking

Description	Requirement	Optical Camera
Field of view	> 20°	26°
Image CubeSats	Need 2 images	58.7 fps

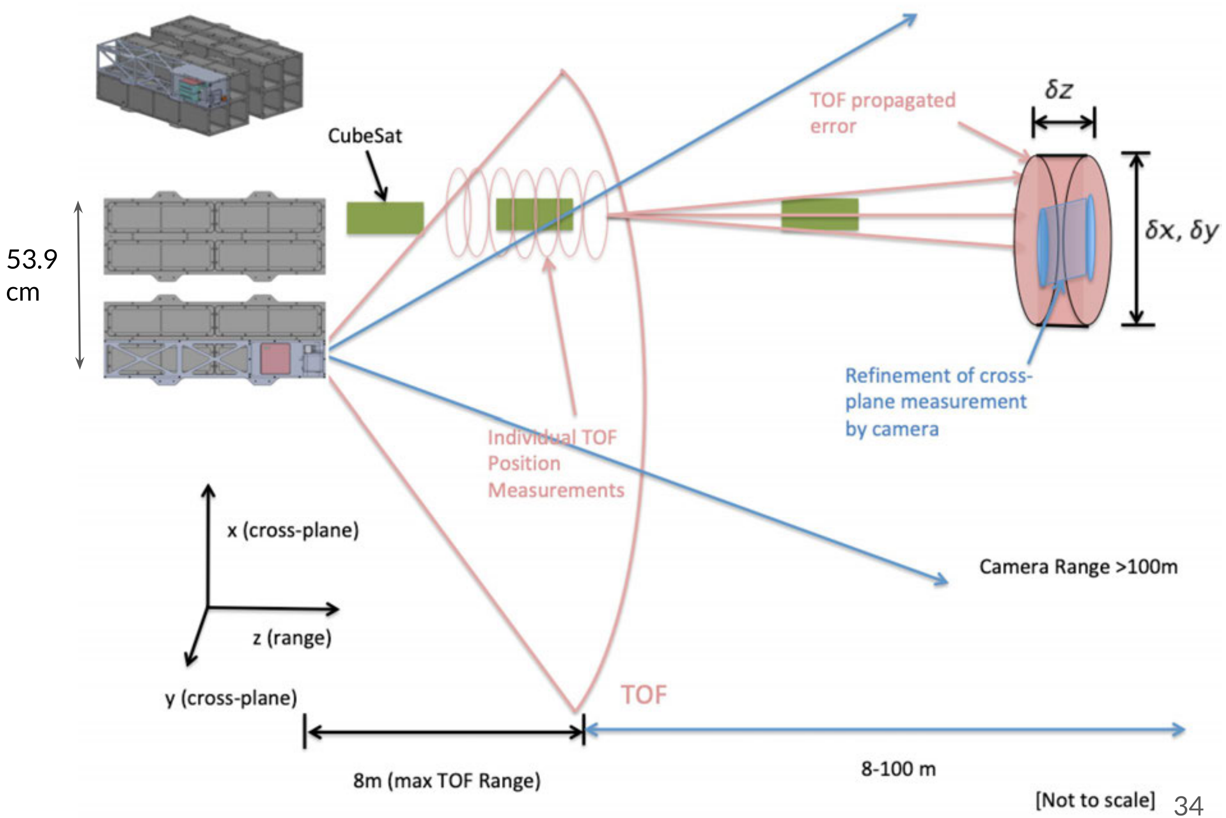
Sensor Design Solution

Primary Instrument: **IR Time of Flight (ToF) Camera**

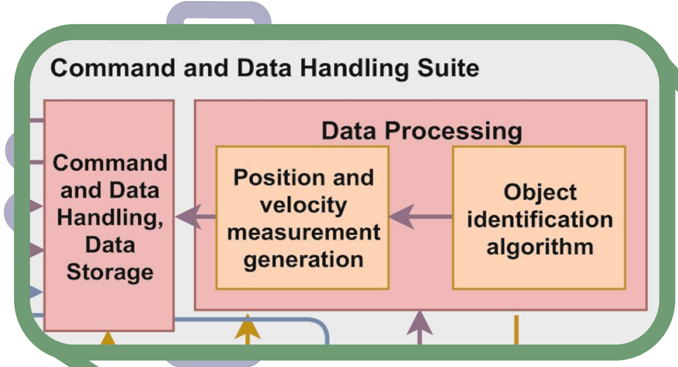
- IR lamp continuously flashing
- *"Echolocation with IR"*
- Provides direct measurement of depth / range
- Data extrapolated forward using linear motion assumption

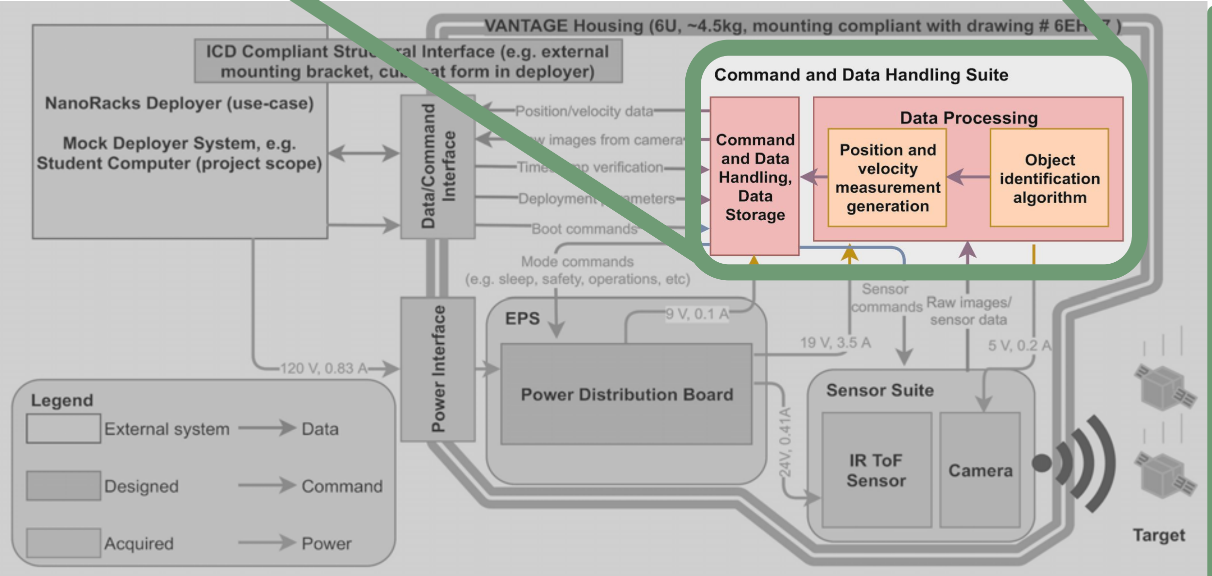
Secondary Instrument: **Small, visual wavelength camera**

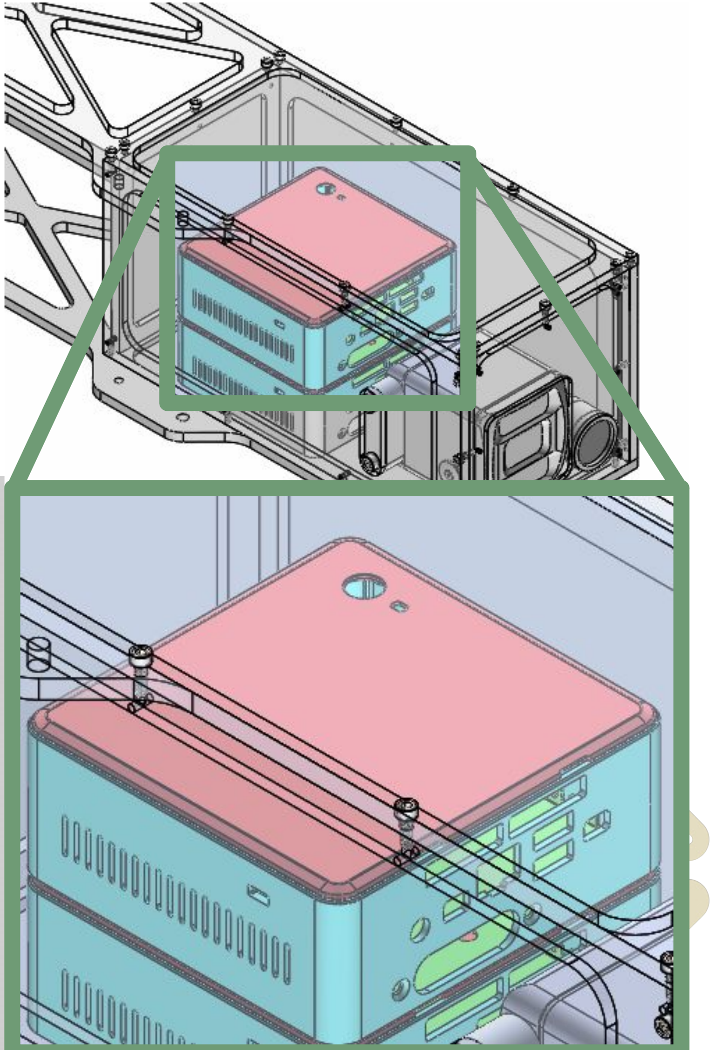
- Provides long-range tracking and cross-range refinement of measurements.



Software Design Solution

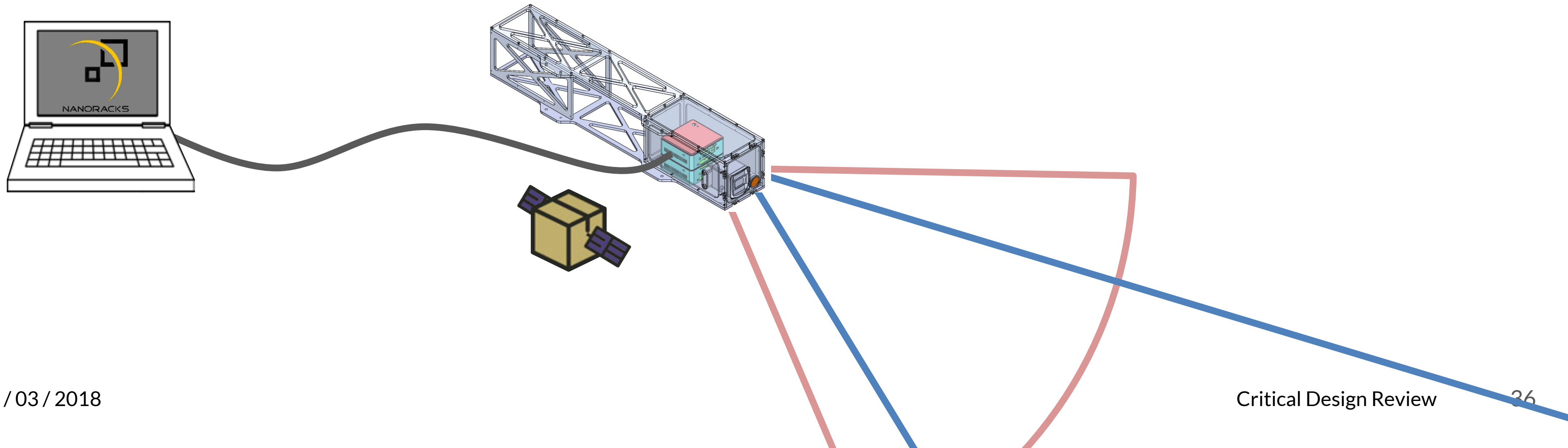






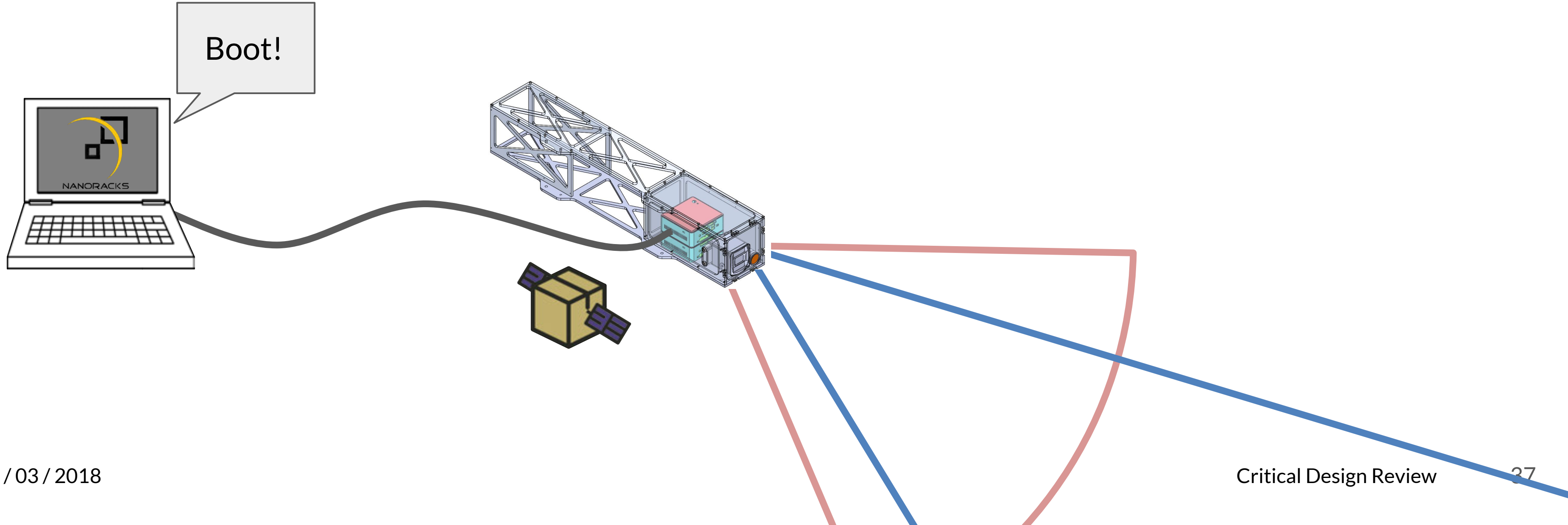
Overall System Software Solution

Boot → Manifest → Pre-Process → Ready! → Go! → Sensing → Post-Process → Output



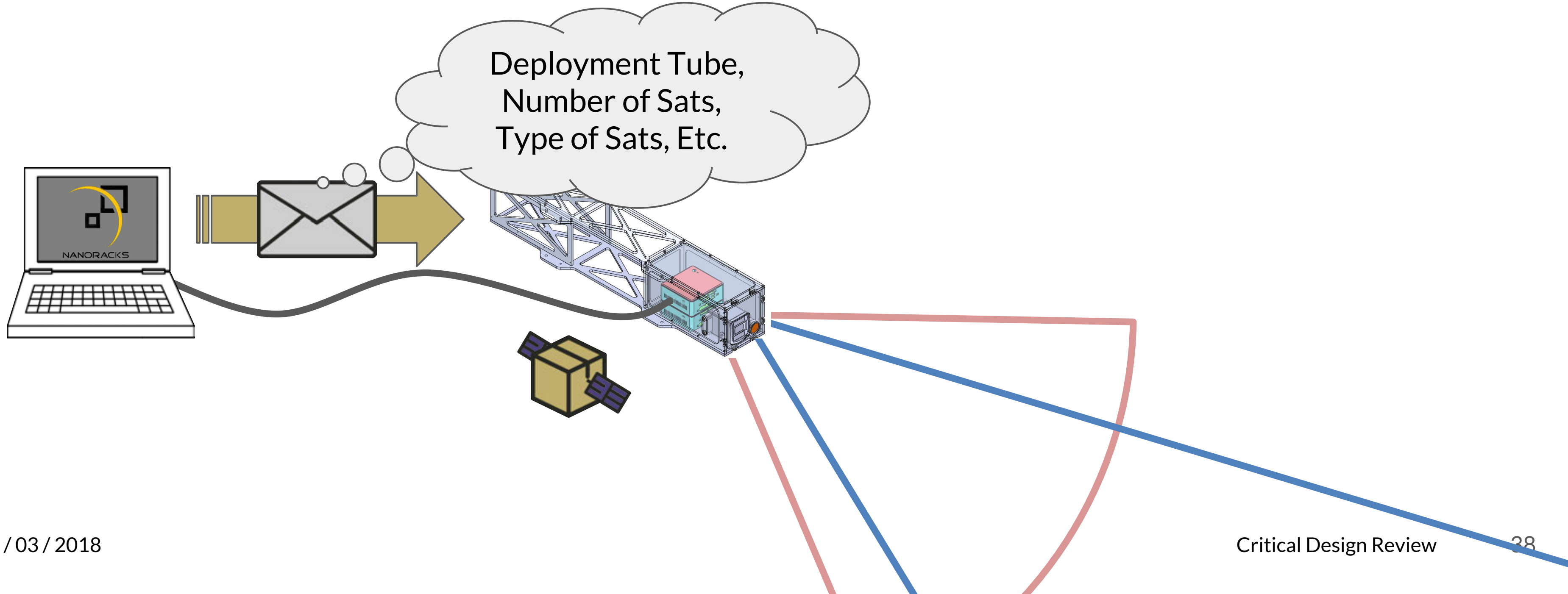
Overall System Software Solution

Boot | Manifest | Pre-Process | Ready! | Go! | Sensing | Post-Process | Output



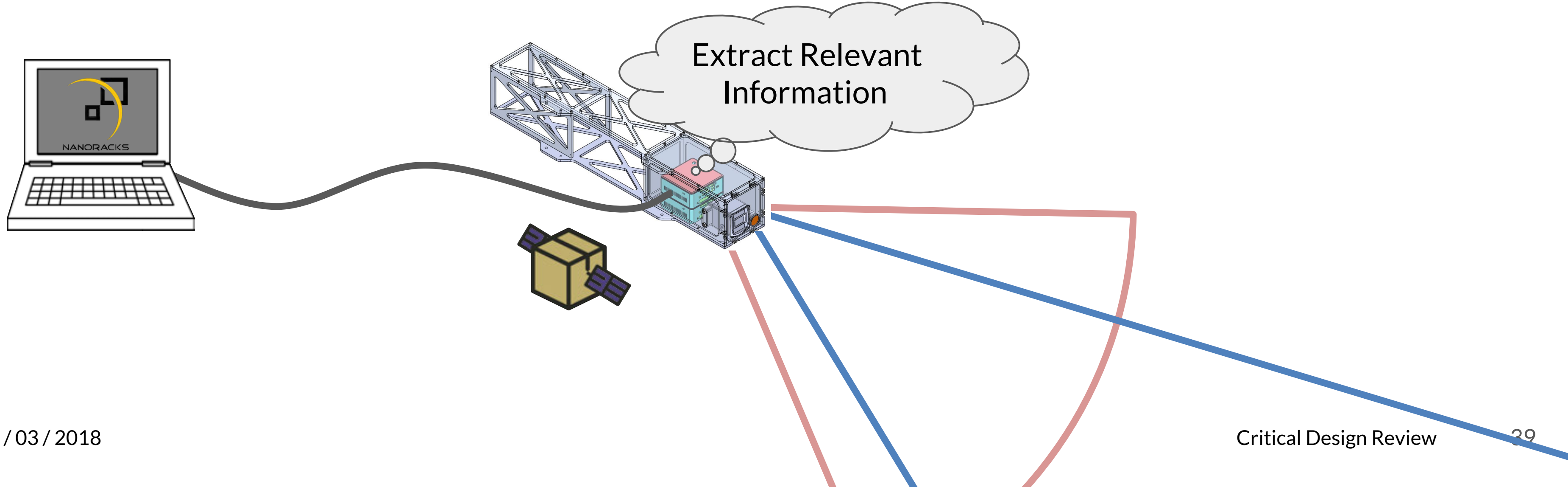
Overall System Software Solution

Boot → **Manifest** → Pre-Process → Ready! → Go! → Sensing → Post-Process → Output



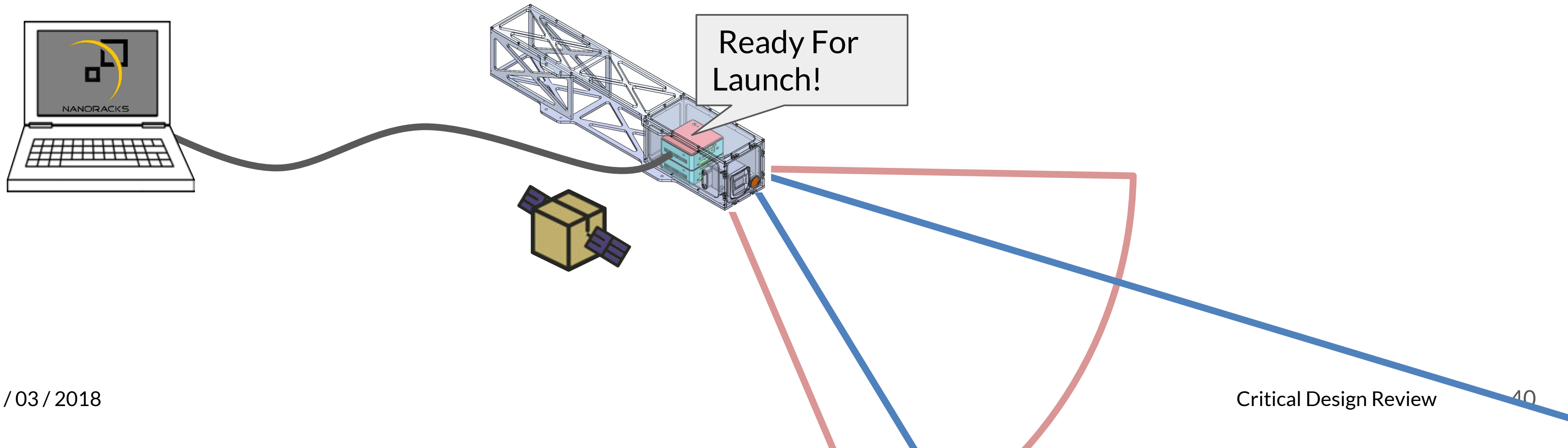
Overall System Software Solution

Boot → Manifest → **Pre-Process** → Ready! → Go! → Sensing → Post-Process → Output



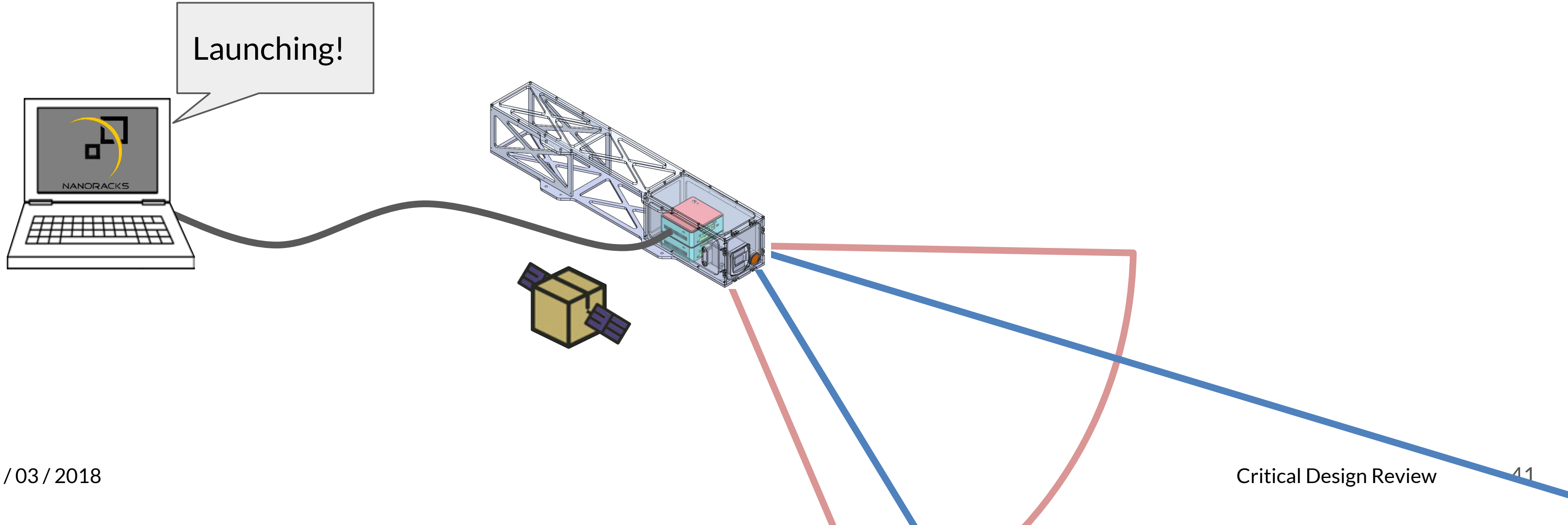
Overall System Software Solution

Boot → Manifest → Pre-Process → **Ready!** → Go! → Sensing → Post-Process → Output



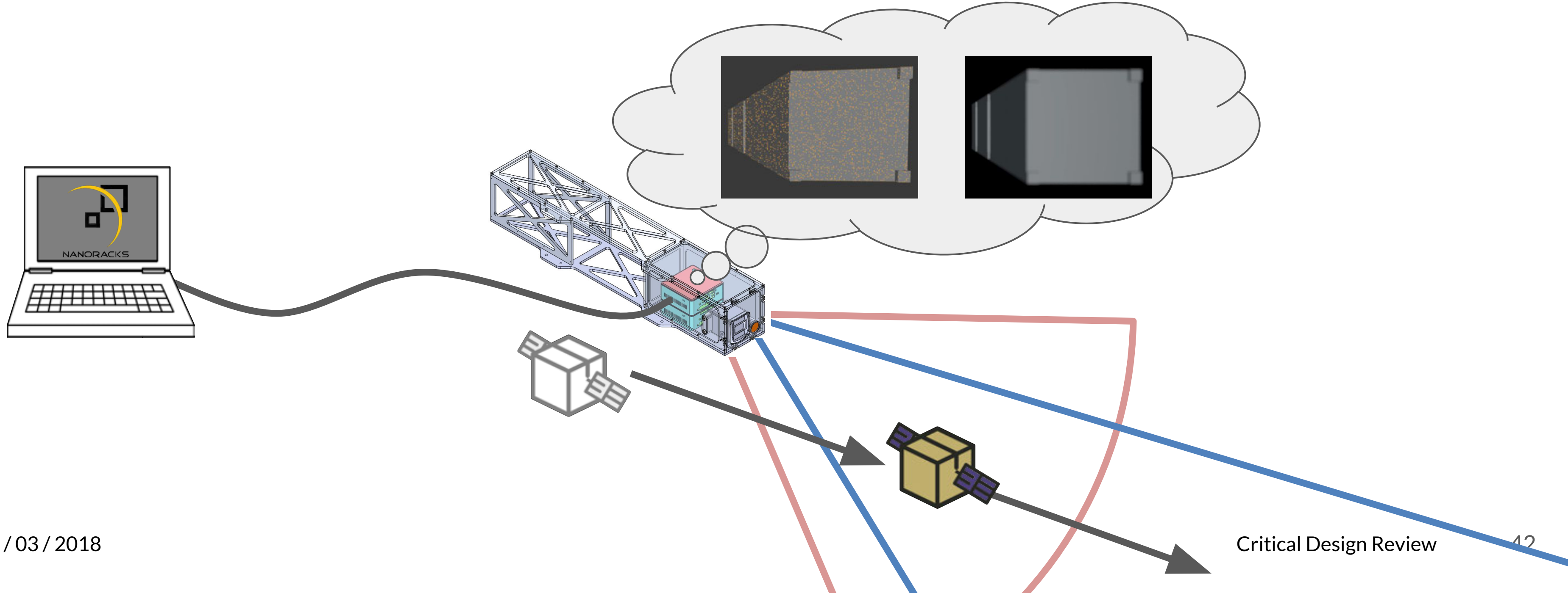
Overall System Software Solution

Boot → Manifest → Pre-Process → Ready! → **Go!** → Sensing → Post-Process → Output



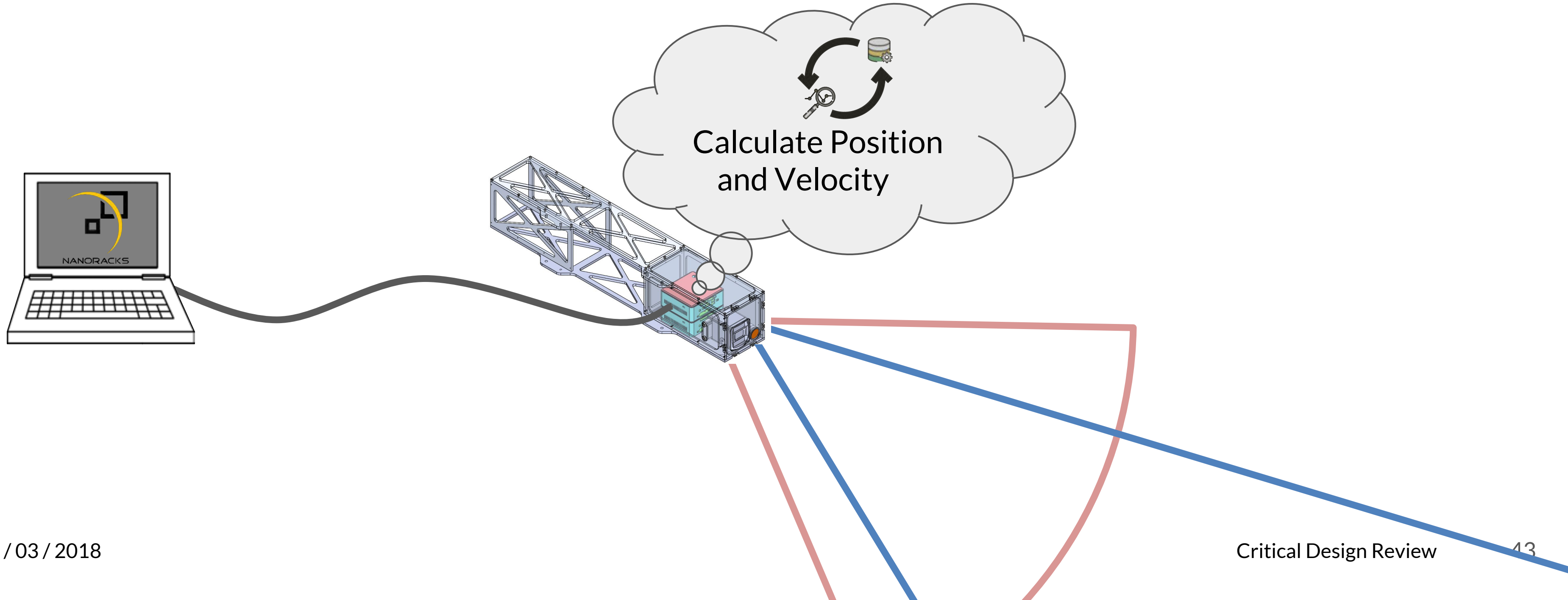
Overall System Software Solution

Boot → Manifest → Pre-Process → Ready! → Go! → **Sensing** → Post-Process → Output



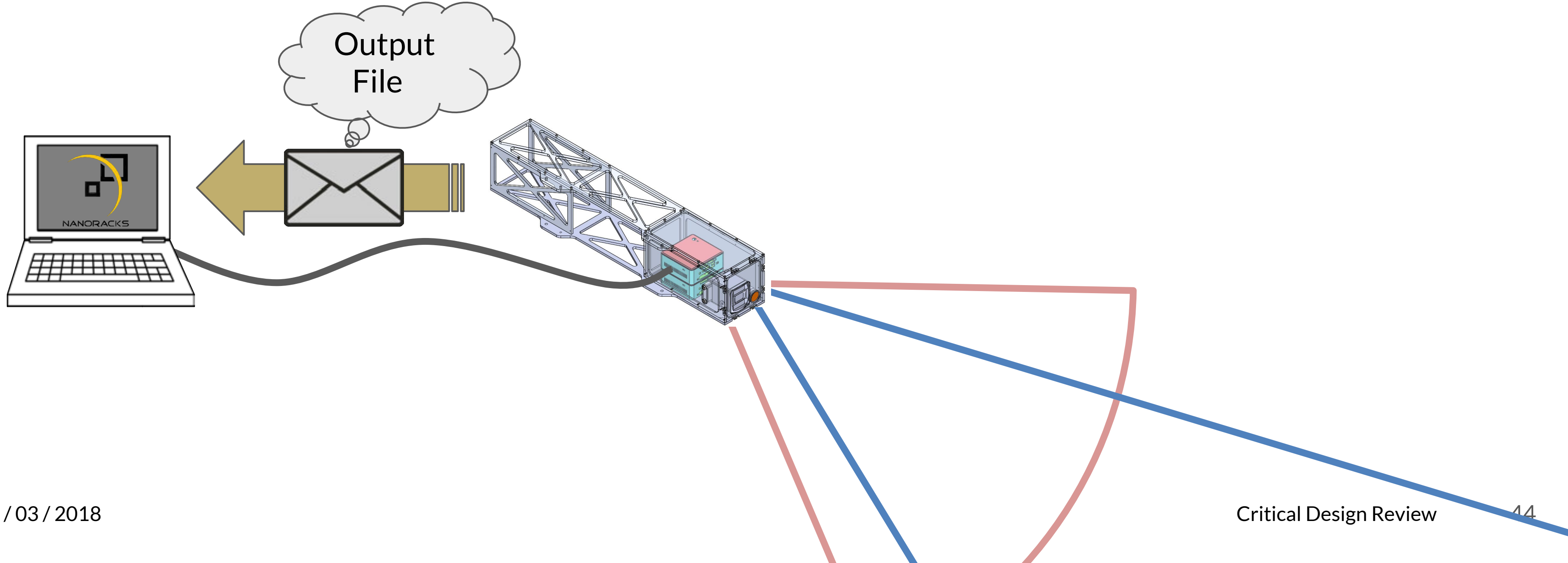
Overall System Software Solution

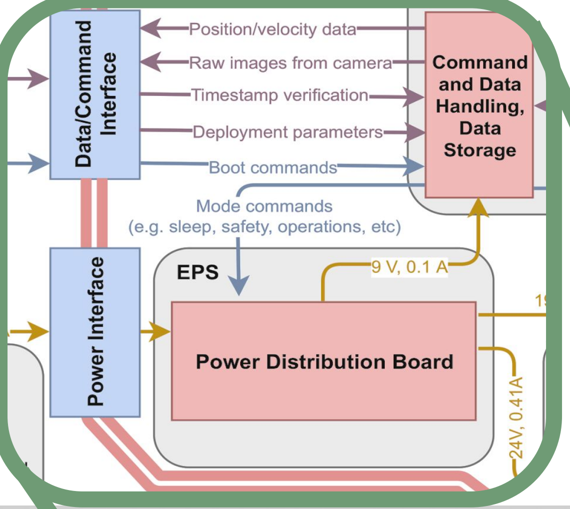
Boot → Manifest → Pre-Process → Ready! → Go! → Sensing → **Post-Process** → Output



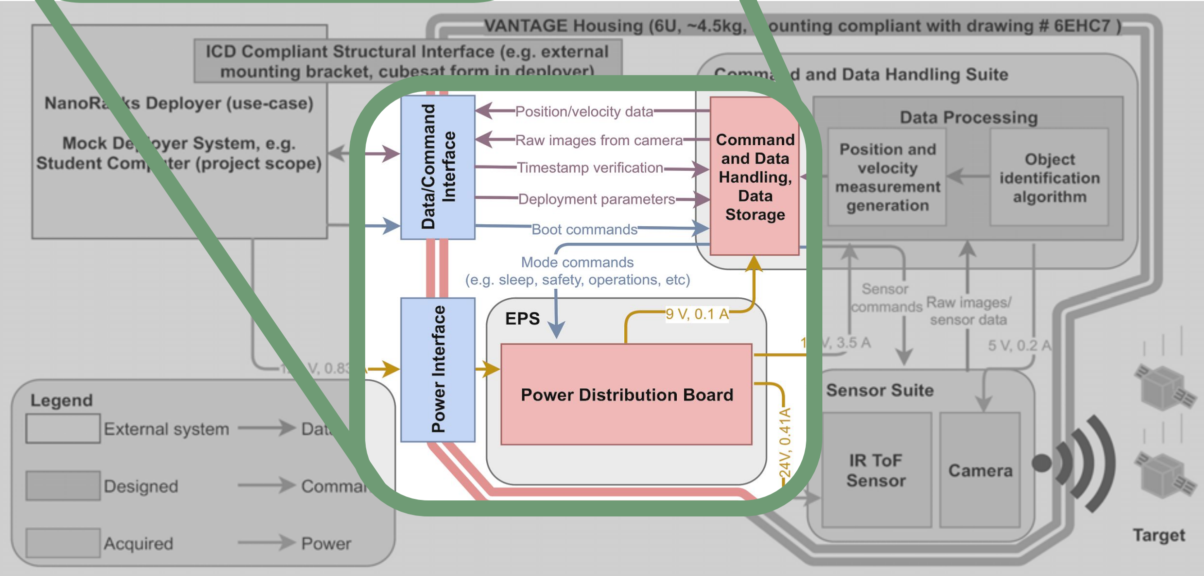
Overall System Software Solution

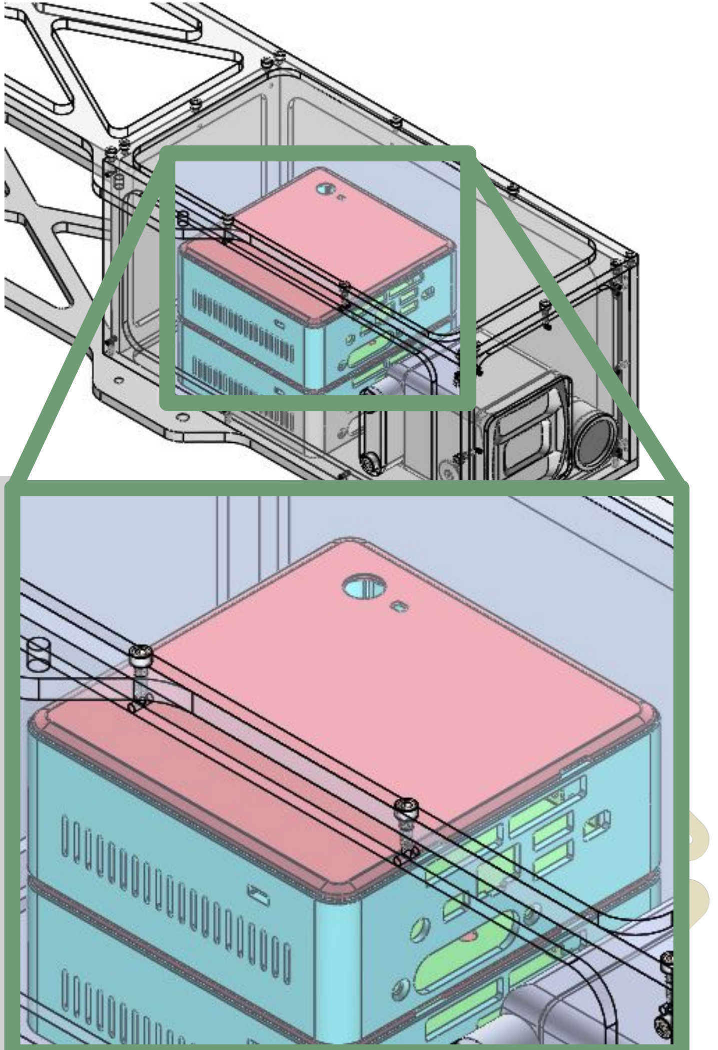
Boot → Manifest → Pre-Process → Ready! → Go! → Sensing → Post-Process → **Output**



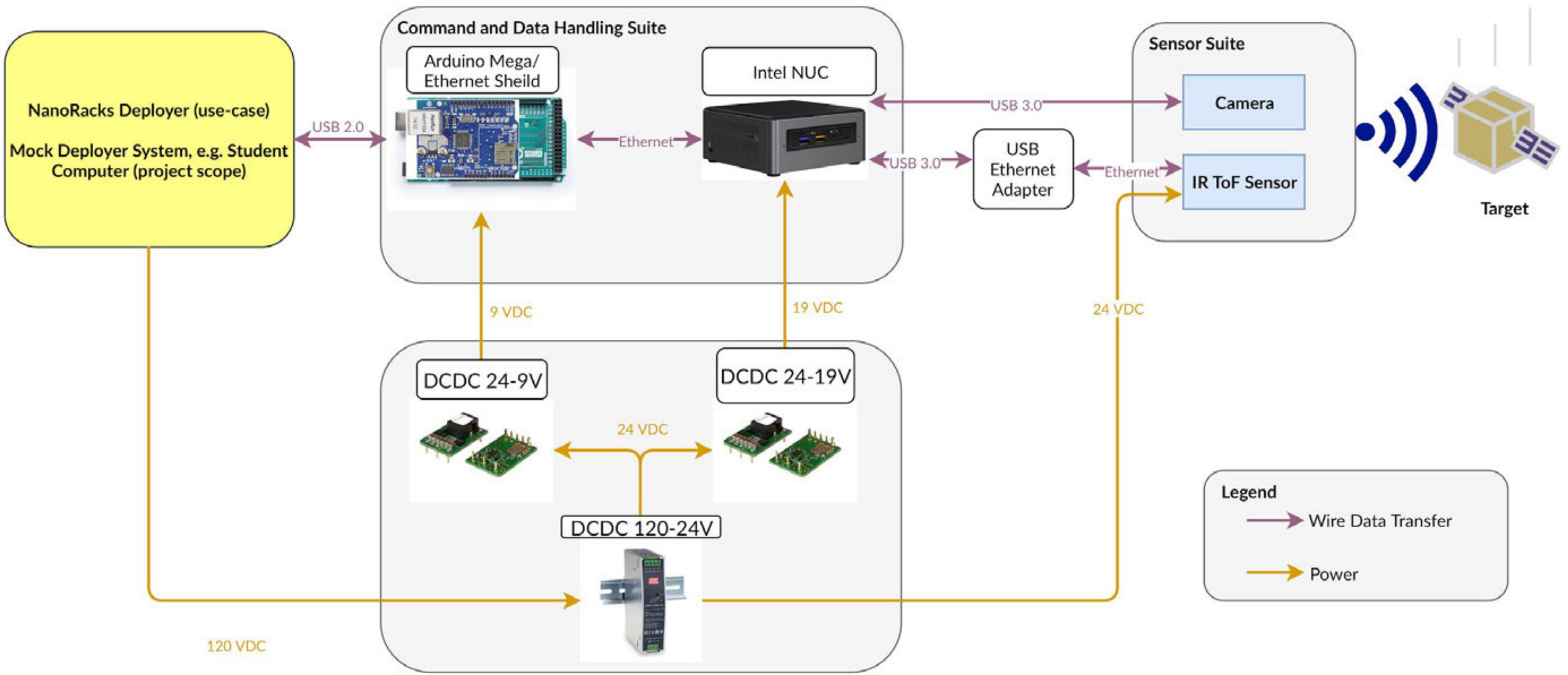


Avionics Design Solution

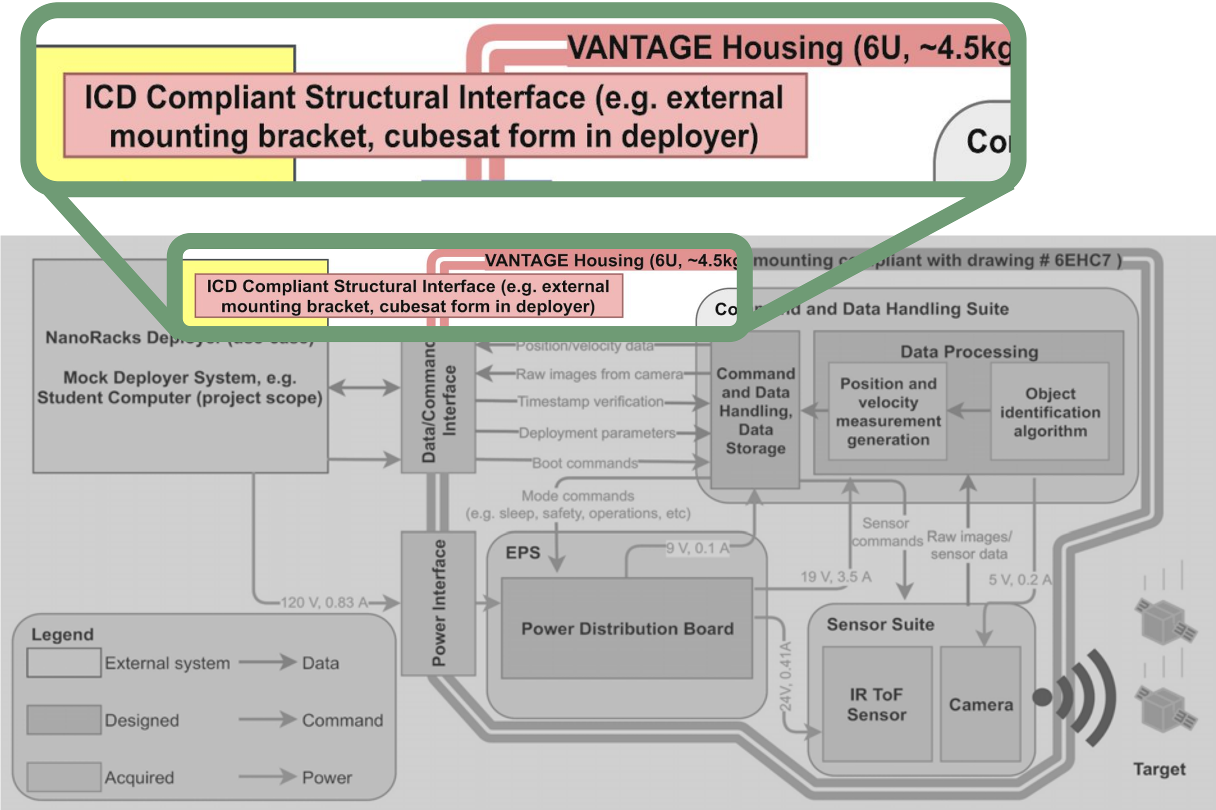


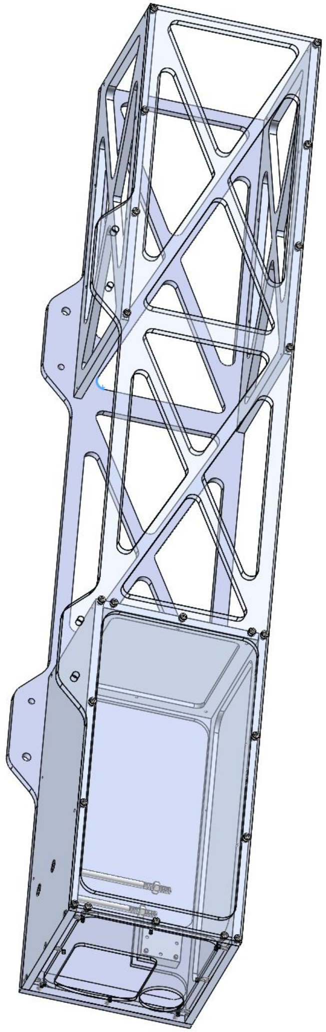


Avionics Solution

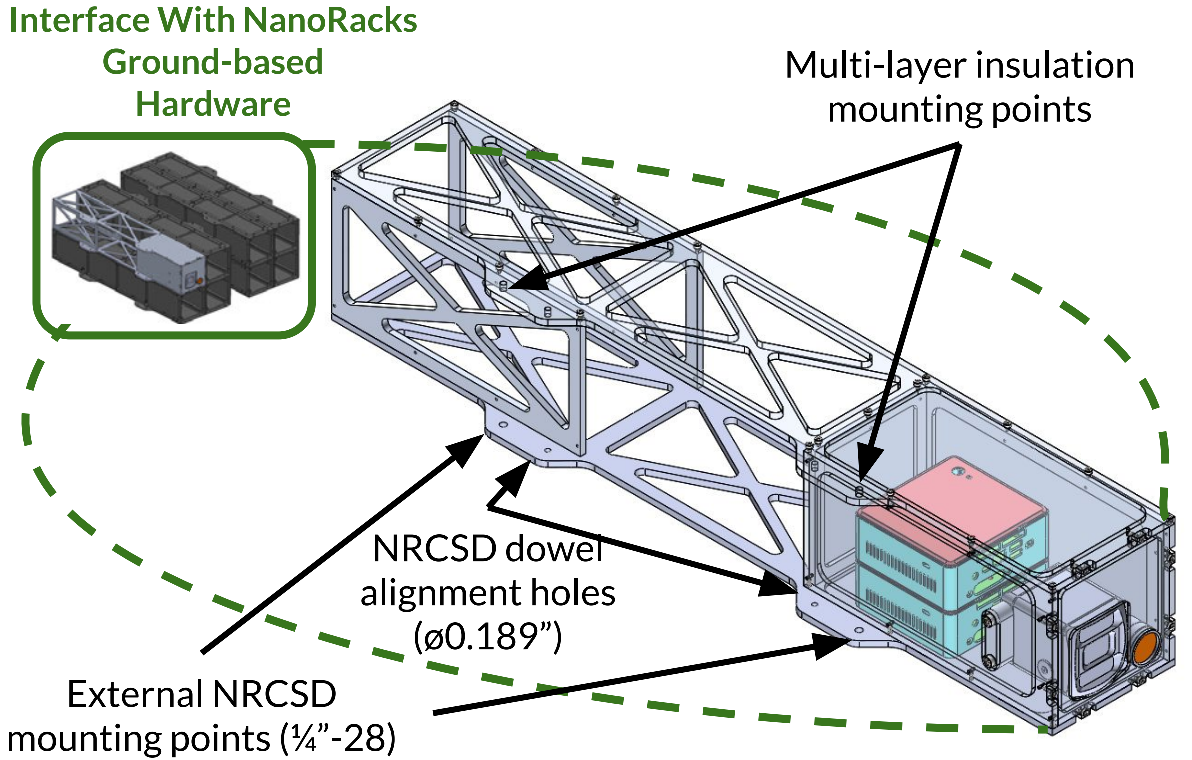


Structural Design Solution





Baseline Design - Structural Interface



- Fills volume of NRCSD silo to interface properly with MLI blanket
  - 5.43”x5.67”x31.89”
- All fasteners torqued and staked
- Mounts according to ICD drawing #63HC7

Requirement	Context
DR.4.1	VANTAGE Mounting Alignment
DR.4.2	VANTAGE Mounting Demonstration

Critical Project Elements

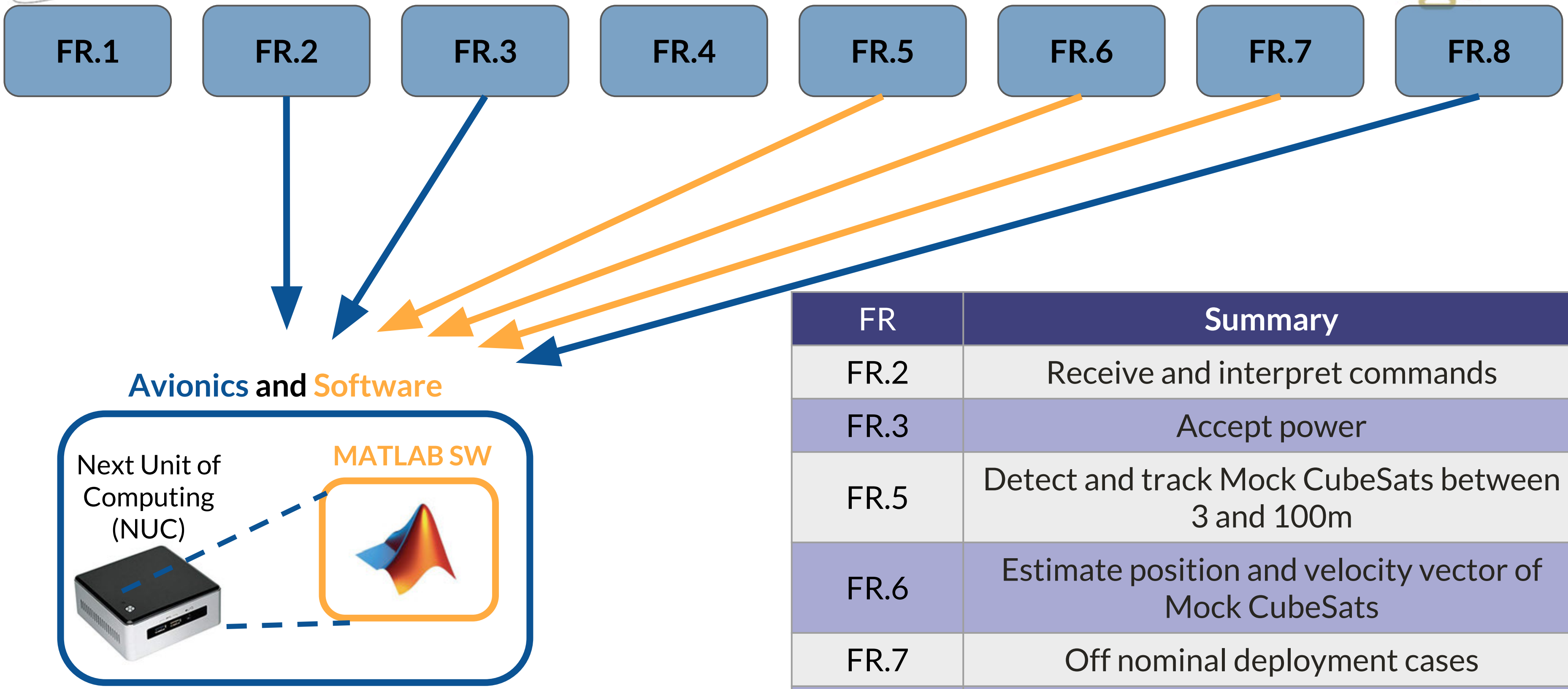
FR Summary

FR	Summary
FR.1	Images of Mock CubeSats between 3 and 100 m
FR.2	Receive and interpret commands
FR.3	Accept power
FR.4	Mechanical Integration
FR.5	Detect and track Mock CubeSats between 3 and 100m
FR.6	Estimate position and velocity vector of Mock CubeSats
FR.7	Off nominal deployment cases
FR.8	Reporting data back to user

CPEs Overview

FR.1 | FR.2 | FR.3 | FR.4 | FR.5 | FR.6 | FR.7 | FR.8

CPEs Overview



FR	Summary
FR.2	Receive and interpret commands
FR.3	Accept power
FR.5	Detect and track Mock CubeSats between 3 and 100m
FR.6	Estimate position and velocity vector of Mock CubeSats
FR.7	Off nominal deployment cases
FR.8	Reporting data back to user

CPEs Overview

FR.1 | FR.2 | FR.3 | FR.4 | FR.5 | FR.6 | FR.7 | FR.8

FR	Summary
FR.1	Images of Mock CubeSats between 3 and 100 m
FR.5	Detect and track Mock CubeSats between 3 and 100m
FR.6	Estimate position and velocity vector of Mock CubeSats
FR.7	Off nominal deployment cases

Acquire Data

Time of Flight (TOF) Camera

Monochrome Camera

Sensors Critical Project Elements

Position and Velocity Accuracy

Subsystem CPEs	Governing Requirement(s)	Parent Functional Requirements	CPE Justification
Error in Position and Velocity Measurements	DR.6.1, 6.2	FR.6: Estimate position and velocity vector of Mock CubeSats	Sensors record sensor data, and choosing the right ones will help us meet requirements.

Req.	Summary
DR 6.1	Position Accuracy (10 cm for 3-10m ,10% of range to 100 m)
DR 6.2	Velocity Accuracy (1 cm/s to 10 m , 10cm/s to 100m)

Software Critical Project Elements

Subsystem CPEs	Governing Requirement(s)	Parent Project Objective(s)	CPE Justification
Object Recognition	DR.5.2	FR.5: Detect and track Mock CubeSats between 3 and 100m	If the software is unable to identify mock CubeSats, it will be unable to measure and associate their trajectories.
Multi-object Tracking	DR.5.2, FR.1	FR.5: Detect and track Mock CubeSats between 3 and 100m	CubeSats are deployed in clusters. VANTAGE will be unable to provide sufficient tracking in the use-case if it cannot track multiple objects in the FOV.

Req.	Summary
DR 5.2	Software shall detect mock CubeSats within FOV at a distance of 3-100m
DR 6.1	Position Accuracy (10 cm for 3-10m ,10% of range to 100 m)
DR 6.2	Velocity Accuracy (1 cm/s to 10 m , 10cm/s to 100m)

Avionics Critical Project Elements

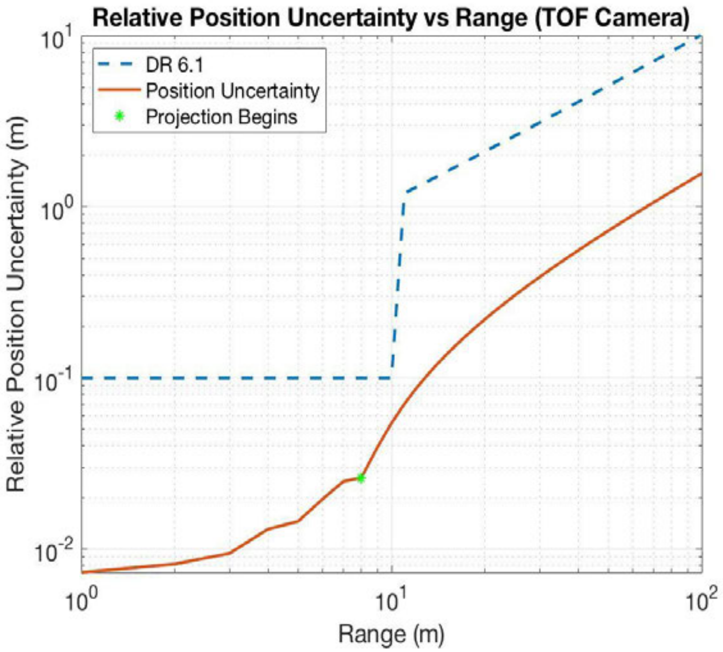
Subsystem CPEs	Governing Requirement(s)	Functional Requirements	CPE Justification
Data Storage and Processing Data	DR.8.1-EL DR.8.2-EL	FR.8: Reporting data back to user	The selected avionics will limit VANTAGE's processing speed and maximum storage capacity, so these factors must be taken into account when selecting hardware.

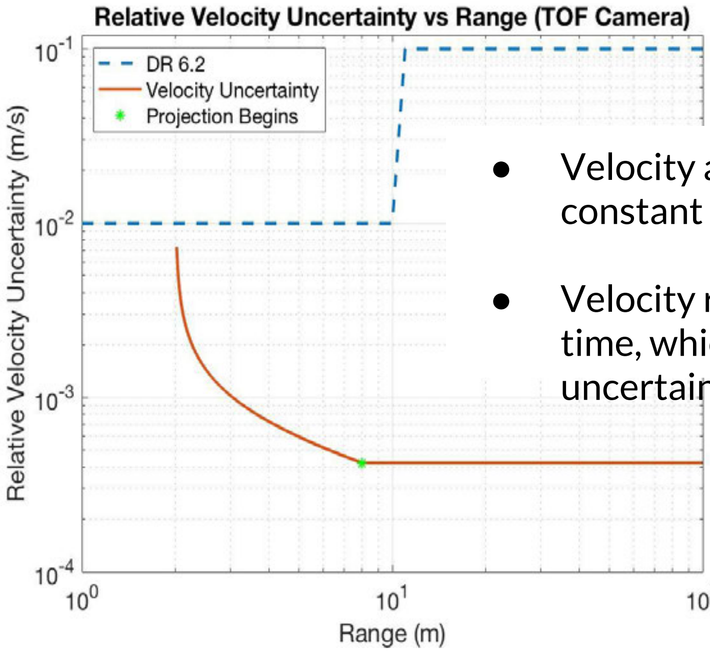
Req. Label	Summary
DR 8.1 EL	The electronics subsystem shall transmit results within 15 minutes of final mock CubeSat deployment.
DR 8.2 EL	The system shall store all images, sensor data, and estimates within an onboard data storage device.

Design Requirements and their Satisfaction

Sensors CPE Satisfaction

TOF Camera: Position/Velocity Accuracy



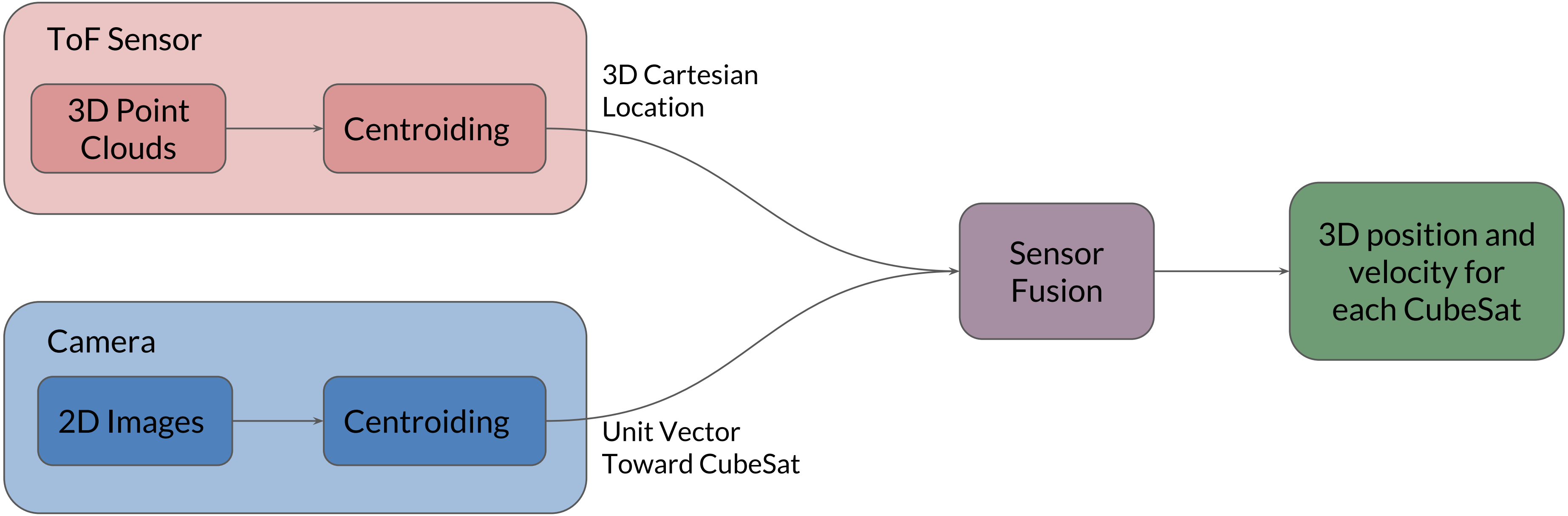


- Velocity assumed constant
- Velocity refined over time, which reduces uncertainty

Req.	Summary
DR 6.1	Position Accuracy (10 cm for 3-10 10m ,10% of range to 100 m)
DR 6.2	Velocity Accuracy (1 cm/s to 10 m , 10cm/s to 100m)

Software CPE Satisfaction

Producing Measurements from Sensor Data



Sensor Simulation Overview

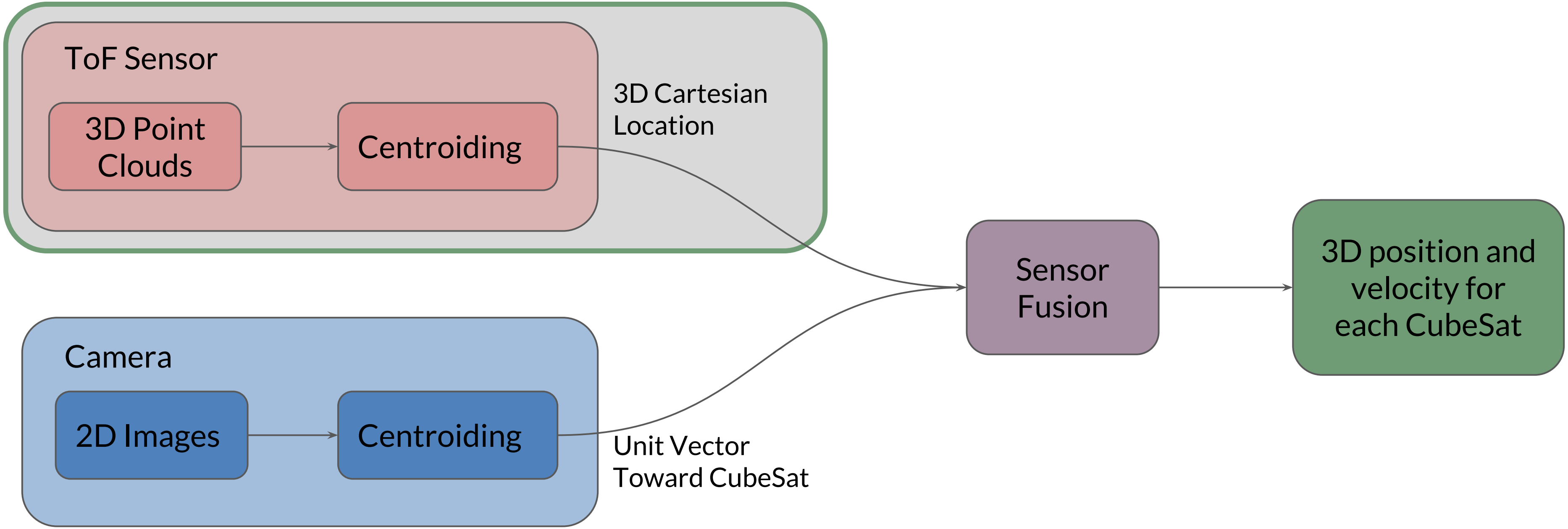
Blensor TOF Camera Simulation

- Simulation producing data representative of our TOF camera

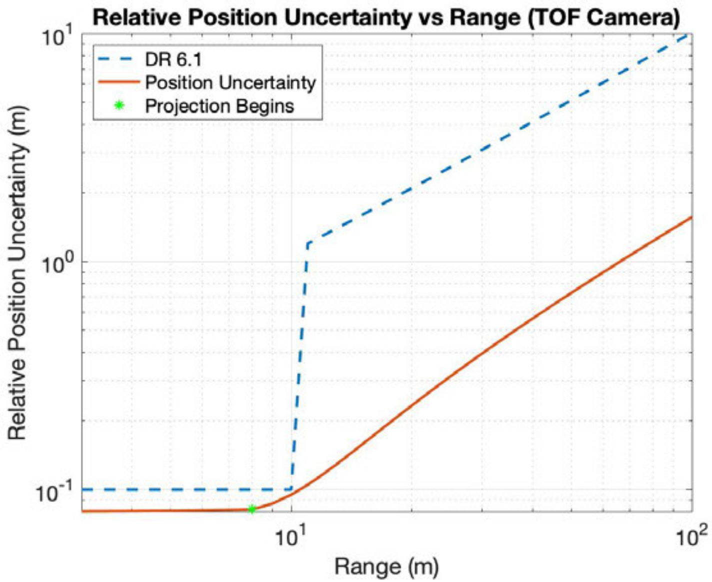
Cinema 4D Optical Camera Simulation

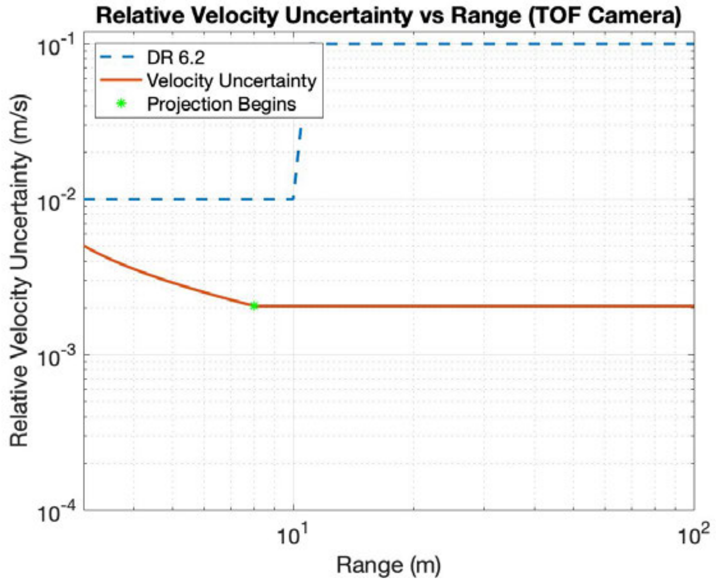
- Industry-standard rendering and animation software producing data representative of our camera

Producing Measurements from Sensor Data



Max Allowable TOF 1σ Error



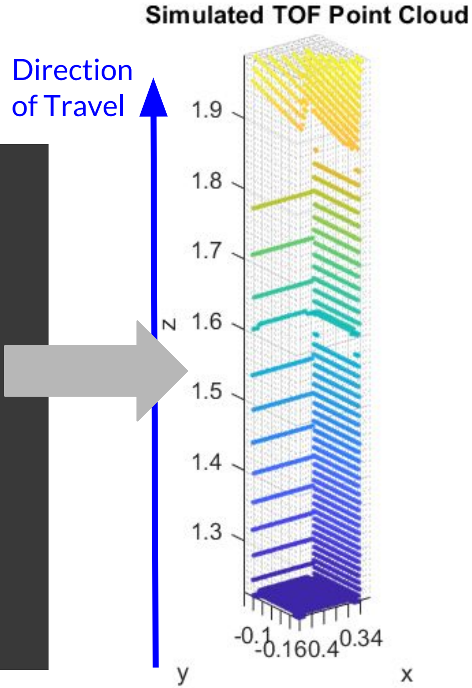


- Error over range with a prescribed TOF 1σ error of 8 cm
- Does satisfy requirements, so **Max Allowable TOF Centroiding Error is 8 cm 1σ**

Req.	Summary
DR 6.1	Position Accuracy (10 cm for 3-10m ,10% of range to 100 m)
DR 6.2	Velocity Accuracy (1 cm/s to 10 m , 10cm/s to 100m)

TOF Centroiding Code Suite

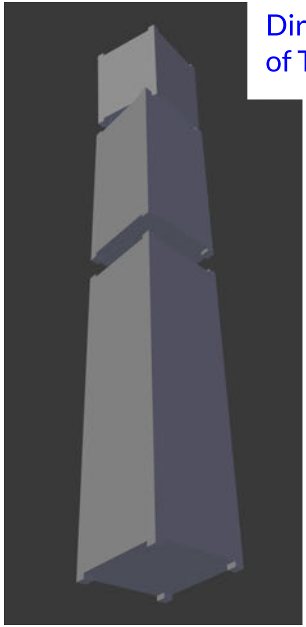
Simulated Deployment



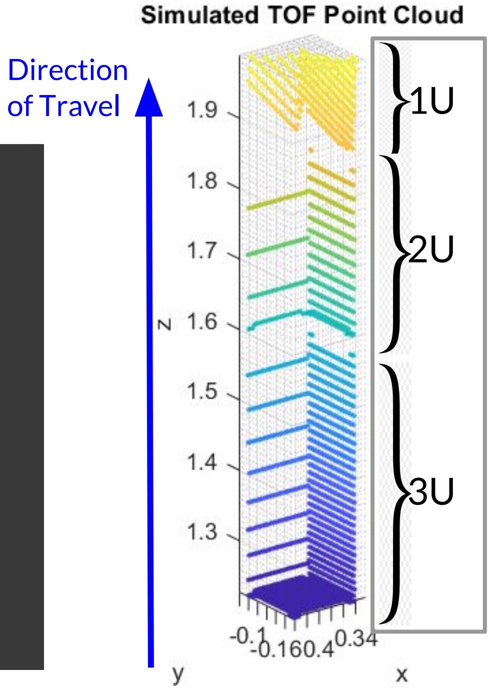
Simulated TOF Point Cloud

- A major part of our project is the ability to:
  - Receive a raw TOF point cloud and deployment order (e.g. 1U 2U 3U)

TOF Centroiding Code Suite



Simulated Deployment

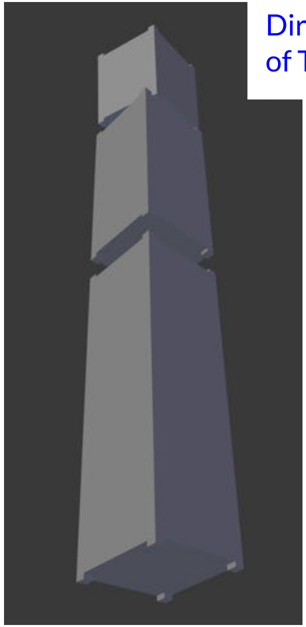


Simulated TOF Point Cloud

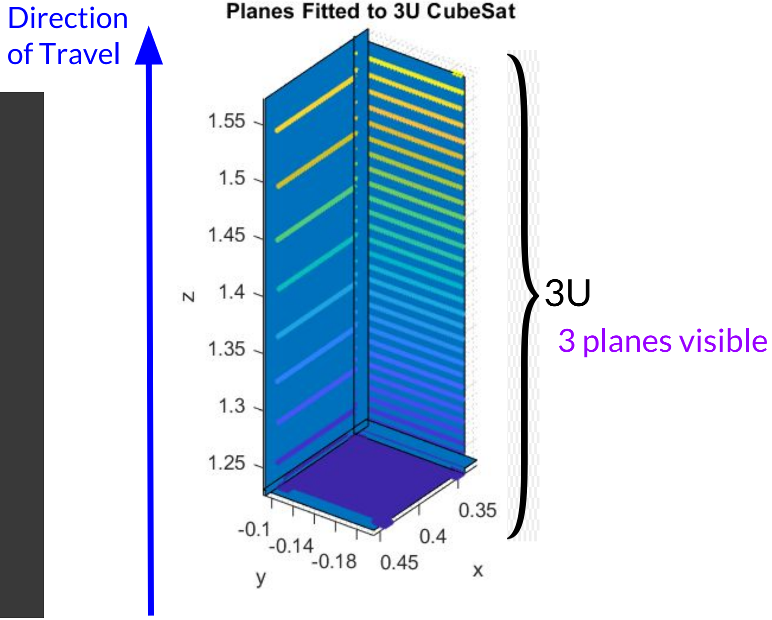
Identified CubeSats

- A major part of our project is the ability to:
  - Receive a raw TOF point cloud and deployment order (e.g. 1U 2U 3U)
  - Identify separate CubeSats

TOF Centroiding Code Suite



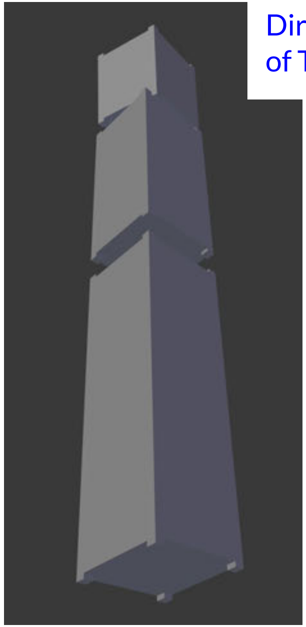
Simulated Deployment

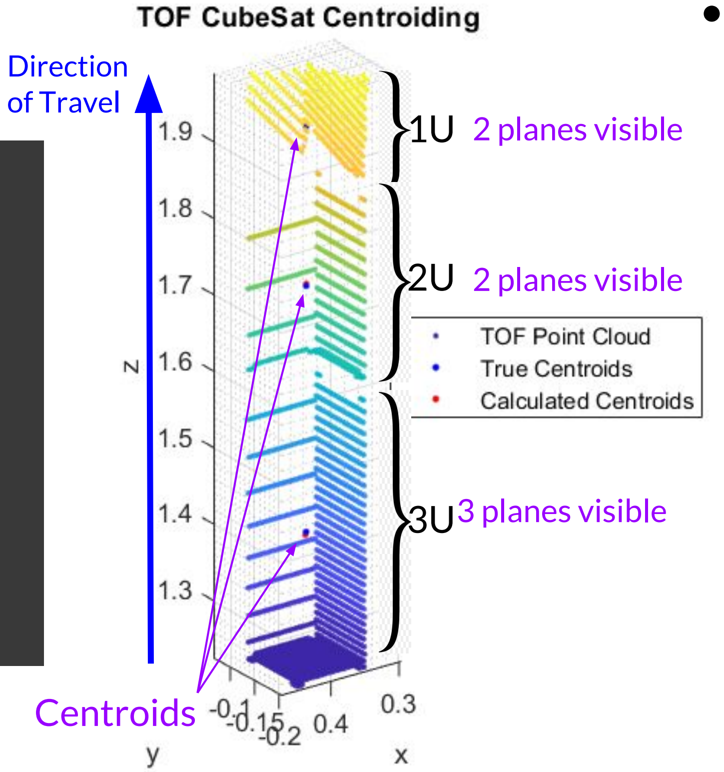


Point Cloud showing Planes fit to 1U CubeSat

- A major part of our project is the ability to:
  - Receive a raw TOF point cloud and deployment order (e.g. 1U 2U 3U)
  - Identify separate CubeSats
  - Identify visible CubeSat planes (shown here only for the 3U)

TOF Centroiding Code Suite

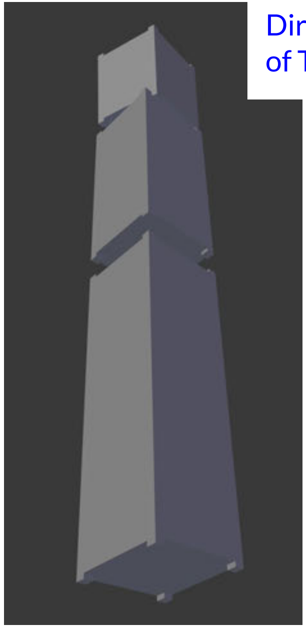


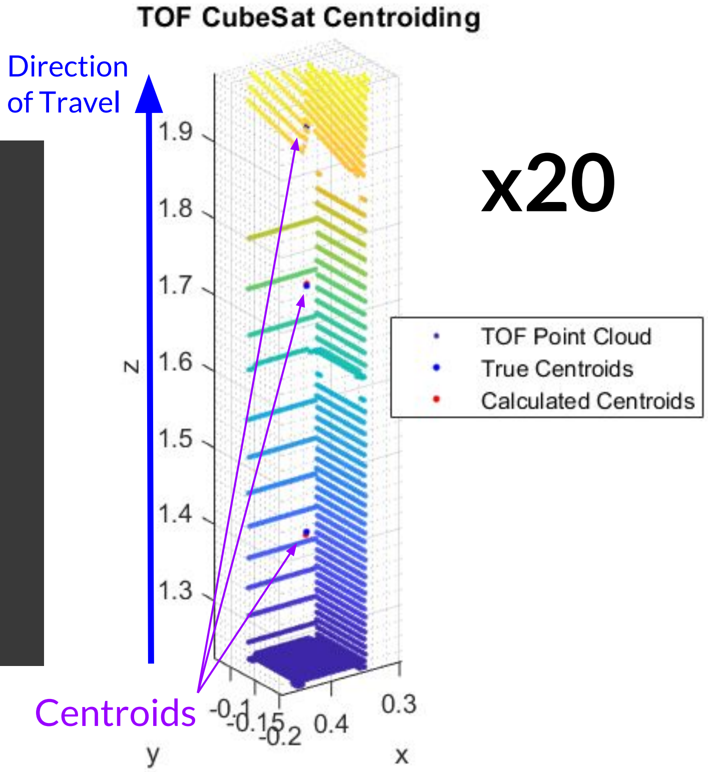


- A major part of our project is the ability to:
  - Receive a raw TOF point cloud and deployment order (e.g. 1U 2U 3U)
  - Identify separate CubeSats
  - Identify visible CubeSat planes
  - Project inward from planes to calculate CubeSat centroids and compare to truth data

CubeSat	Centroid Error (cm)	Max Allowable Error (cm)
1U (tumbling)	0.701	8
2U	0.268	8
3U	0.973	8

TOF Centroiding Code Suite





x20

- Centroid error for a 1U CubeSat over ~20 frames:

CubeSat	Centroid Error Standard Deviation (cm)	Max Allowable 1σ Error (cm)
1U	0.329	8

- Important Takeaways:
  - **The suite has been written and is functional**
  - **Error satisfies requirements**

In Backup:

- Technical methods
- Additional Cases
- Future Work

Working with Real TOF Data

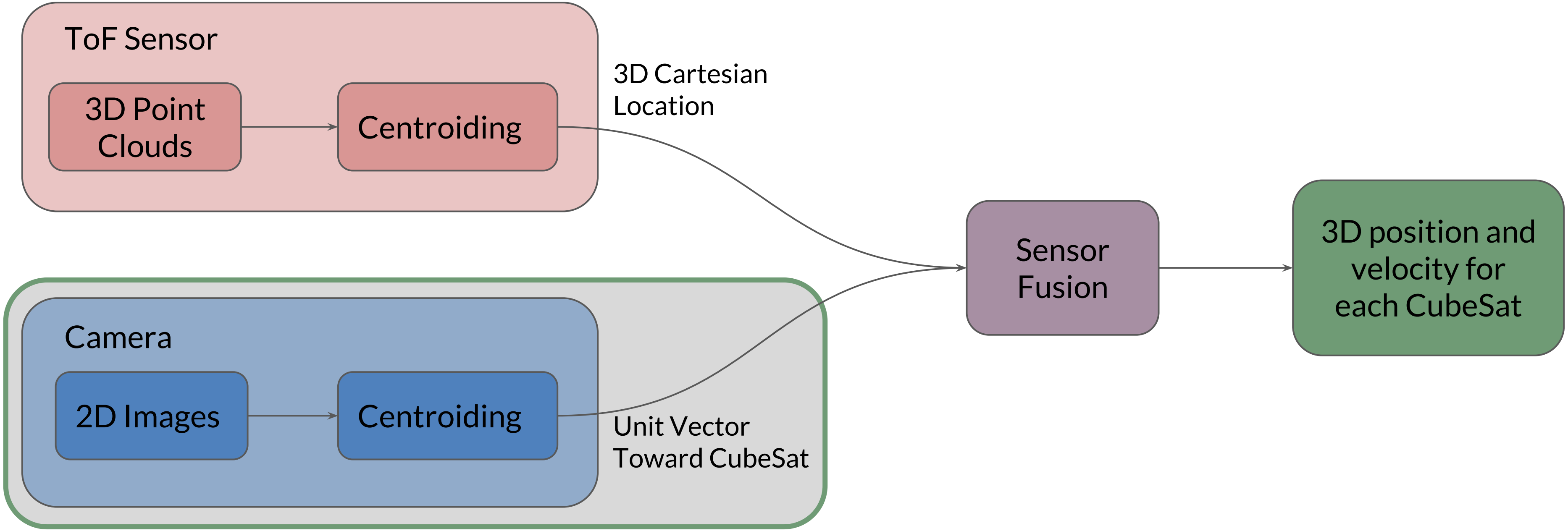
Physical Test Setup

Raw Point Cloud from Physical Test

Planes fitted to Raw Point Cloud and Calculated Centroid

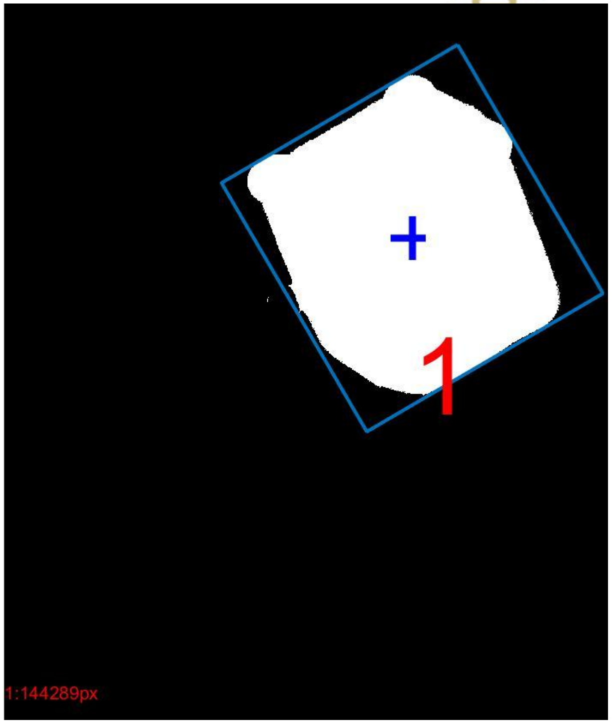
Calculated Centroid

Producing Measurements from Sensor Data



Object Detection

- Ability to detect object centroids was demonstrated in PDR
- A boundary box method has been implemented to improve performance
- Centroid location is determined by the mean of the boundary box locations

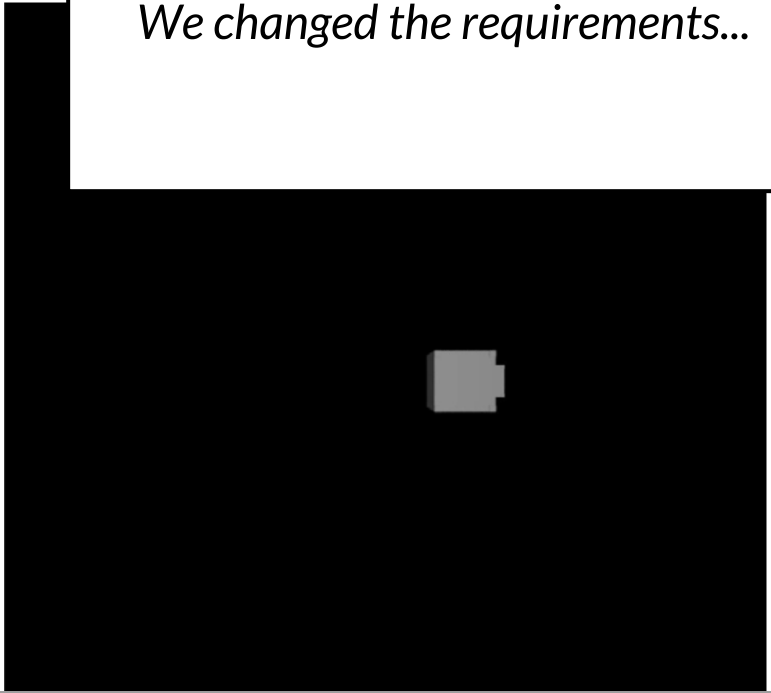


Req.	Summary
DR 5.2	Software shall detect mock CubeSats within FOV at a distance of 3-100m

Object Detection

- When there is occlusion in the image, object detection must be able to ignore partially occluded cubesats from the centroid calculations

We changed the requirements...



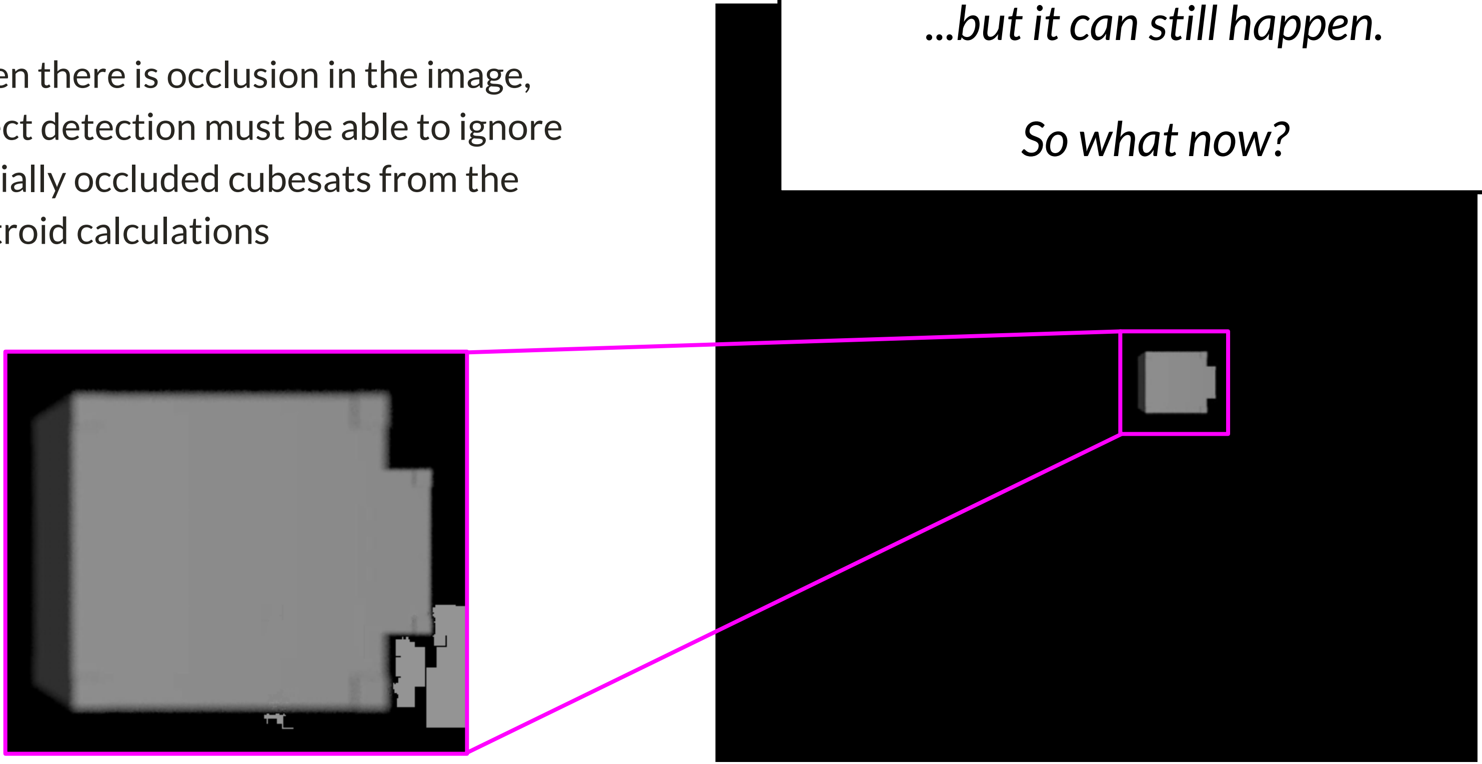
Req.	Summary
DR 5.2	Software shall detect mock CubeSats within FOV at a distance of 3-100m

Object Detection

- When there is occlusion in the image, object detection must be able to ignore partially occluded cubesats from the centroid calculations

...but it can still happen.

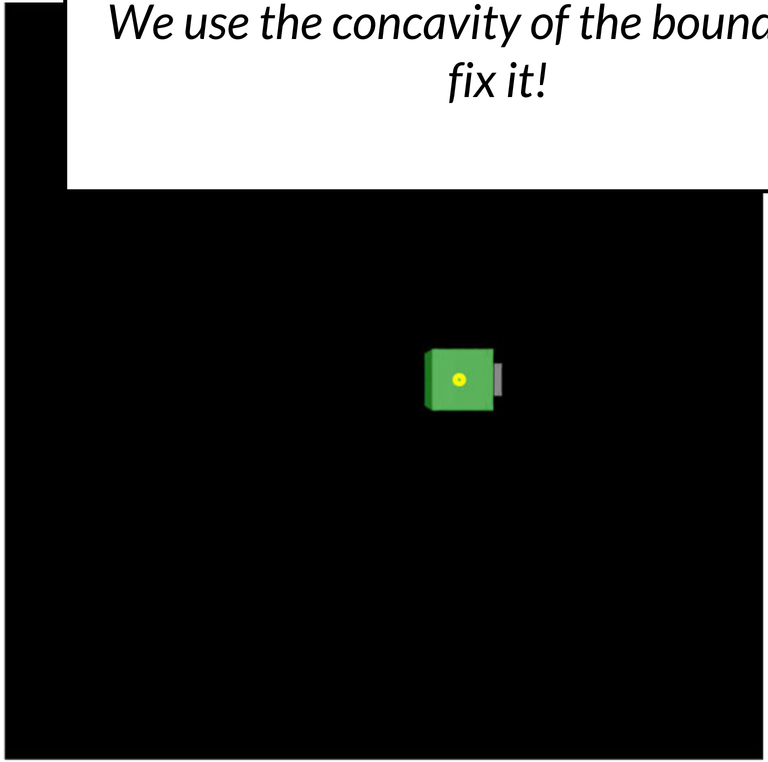
So what now?



Object Detection

- Using geometric properties such as boundary concavity, we are able to exclude the partially obfuscated cubesat from the centroid calculation for the cubesat in front

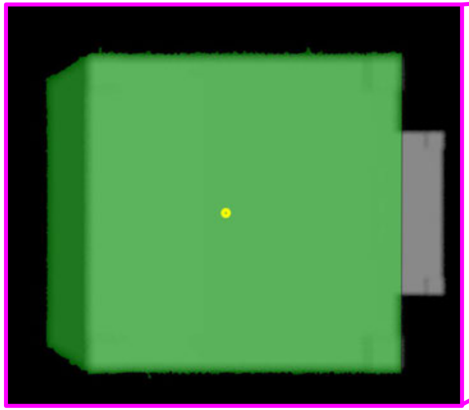
We use the concavity of the boundary to fix it!

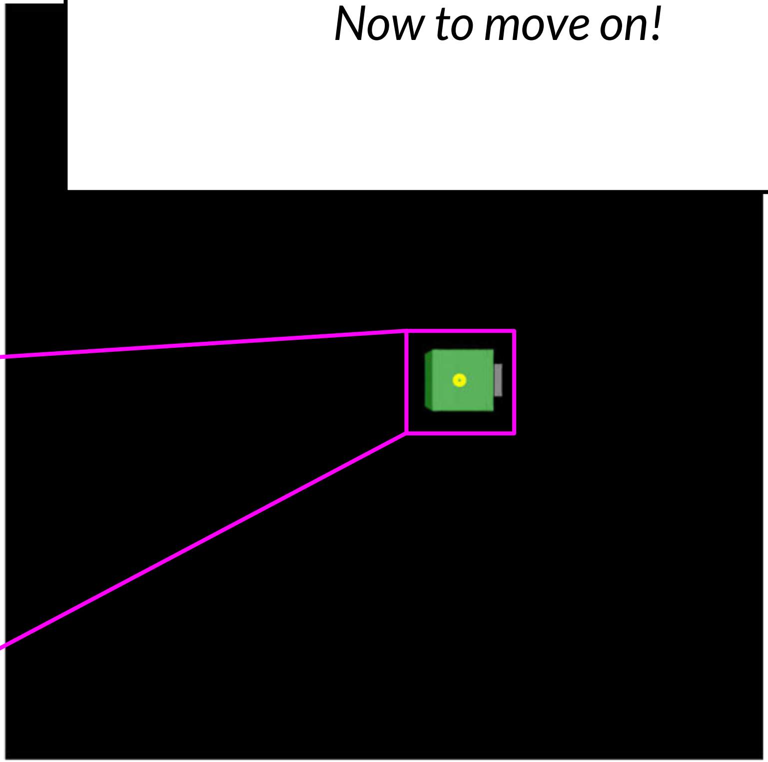


Object Detection

- Using geometric properties such as boundary concavity, we are able to exclude the partially obfuscated cubesat from the centroid calculation for the cubesat in front

Now to move on!

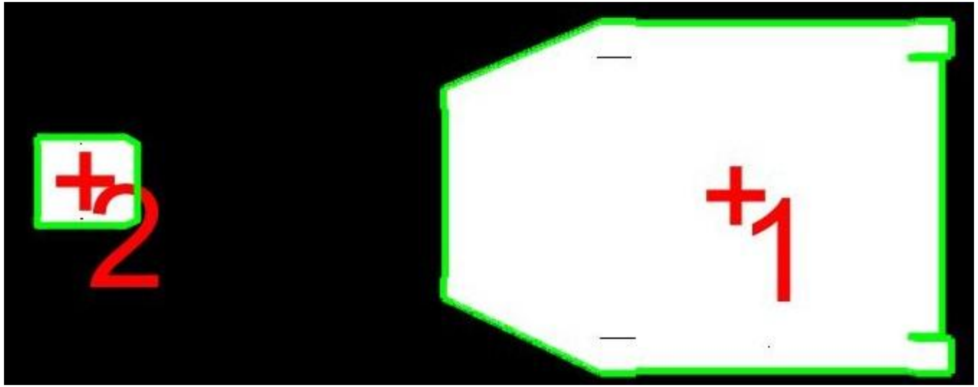




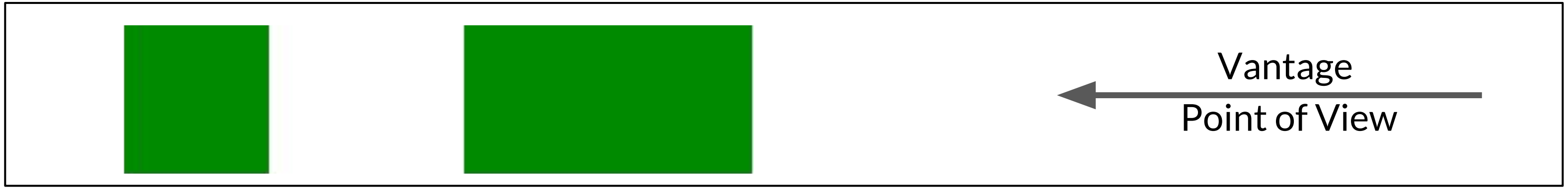
Multi-Object Tracking

- We use a heuristic 1-nearest neighbor approach for centroid association.

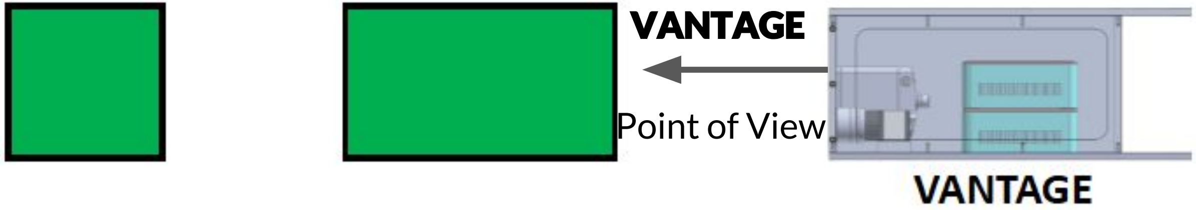
- When there is no occlusion we use a nearest neighbor algorithm with the camera projection as the feature space.



Side view of the two cubesats



Multi-Object Tracking



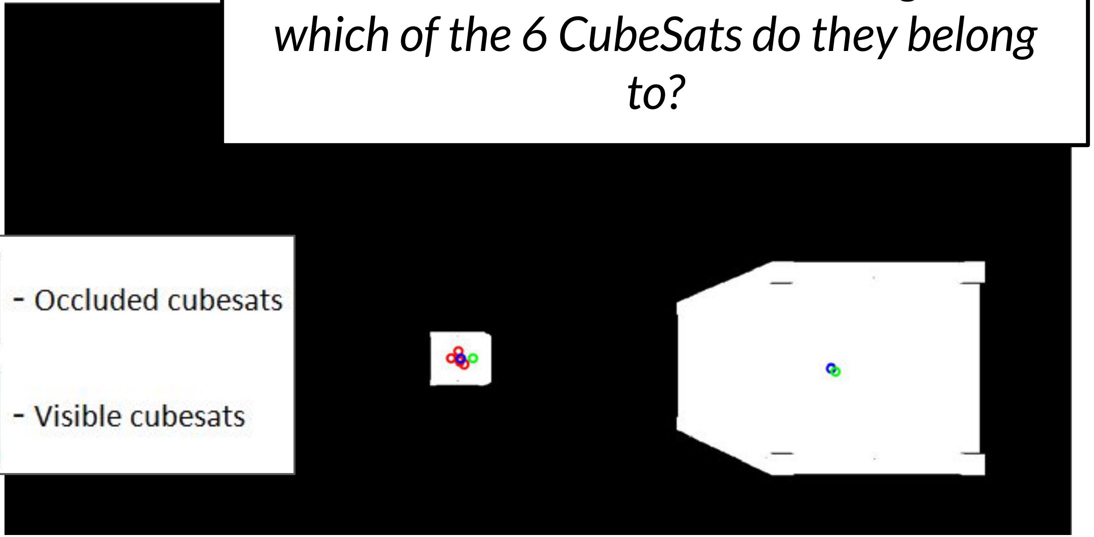
Why track two, when we can track six?

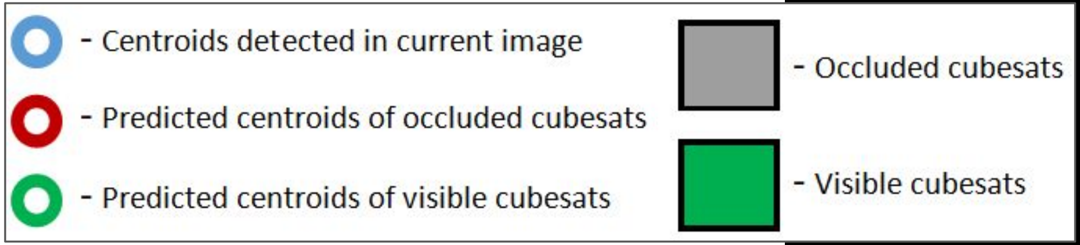
Gray CubeSats are occluded and not visible to Vantage.

Multi-Object Tracking

We found 2 centroids in the image, but which of the 6 CubeSats do they belong to?

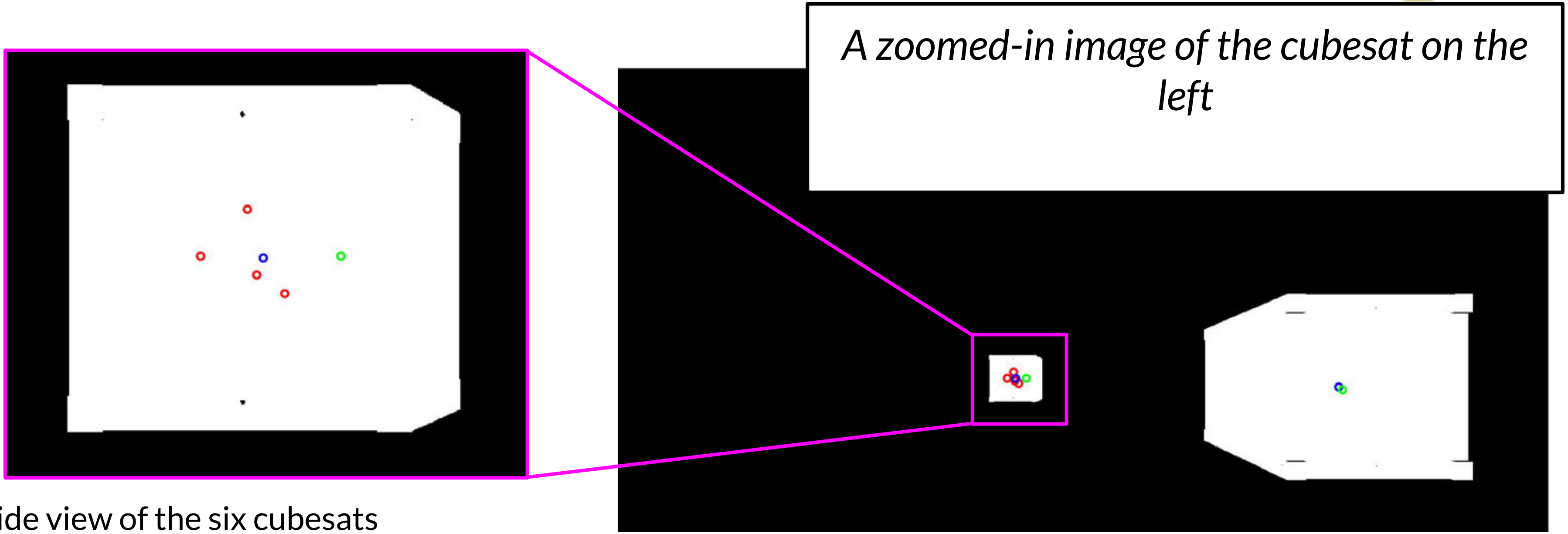
- When there is occlusion we use the heuristic that the closest object is the object visible.





Side view of the six cubesats

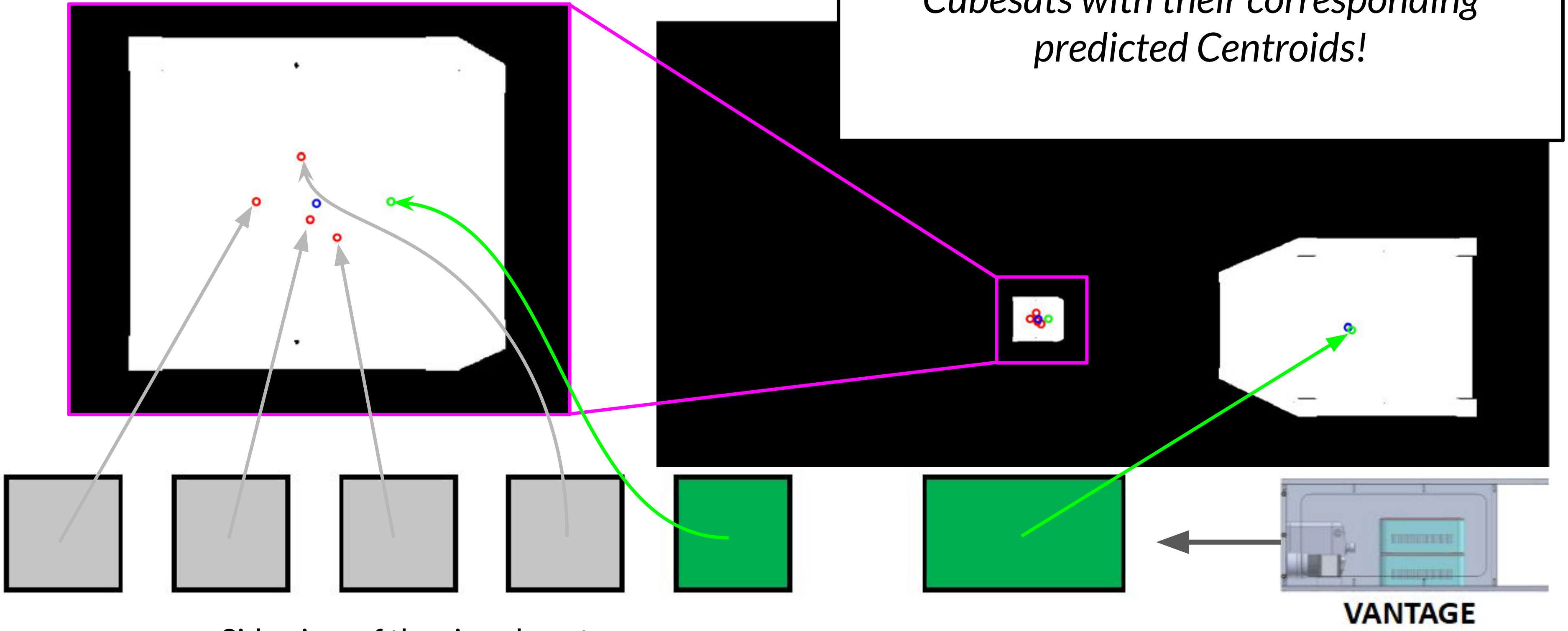
Multi-Object Tracking



Side view of the six cubesats

Multi-Object Tracking

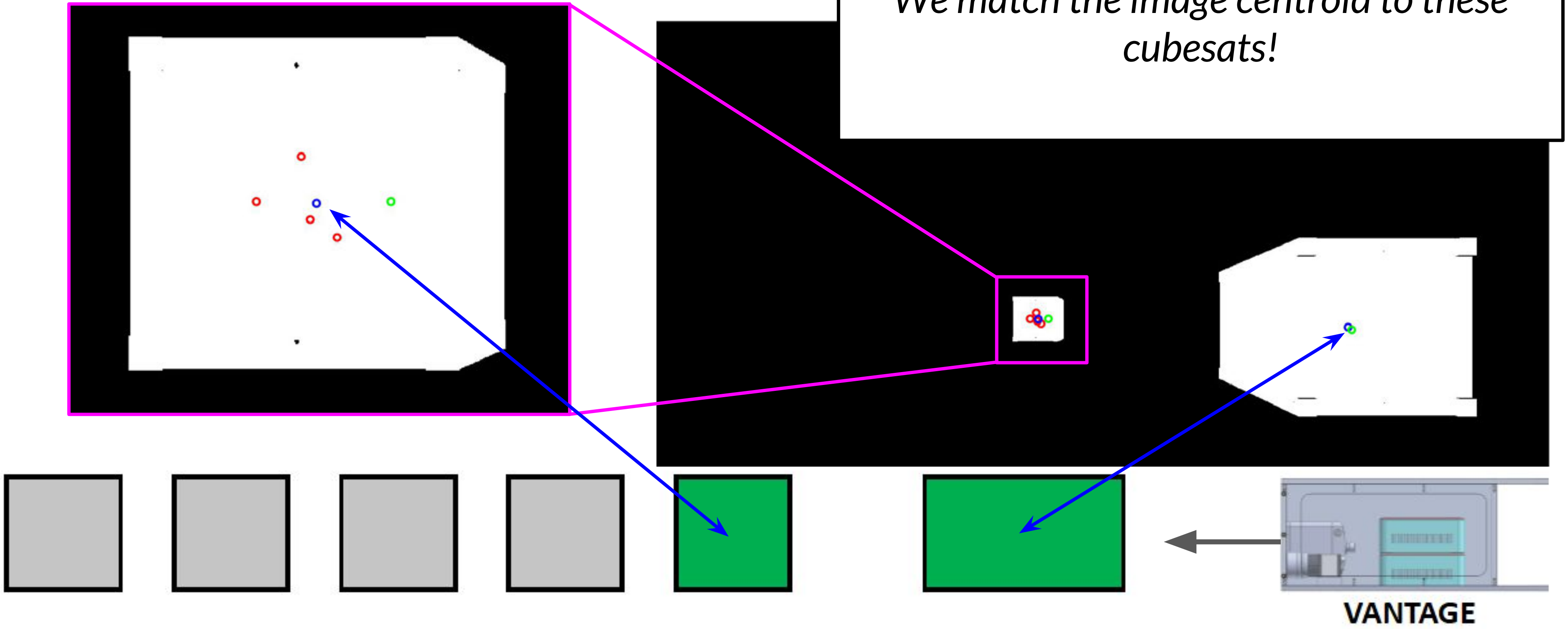
Cubesats with their corresponding predicted Centroids!



Side view of the six cubesats

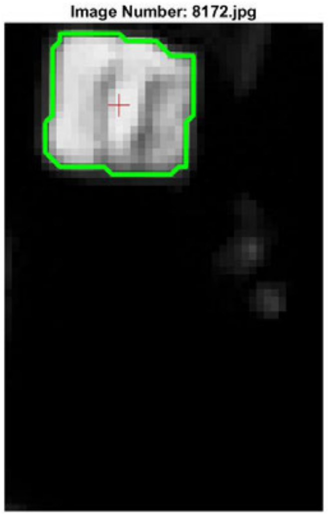
Multi-Object Tracking

We match the image centroid to these cubesats!

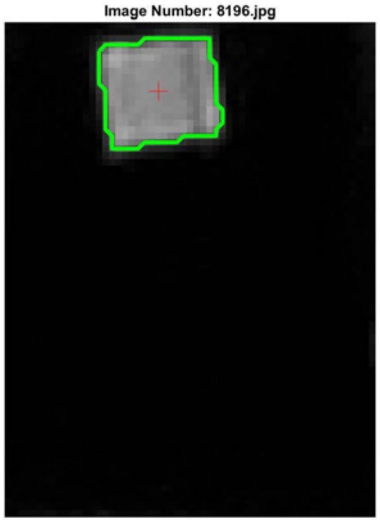


Camera Tracking

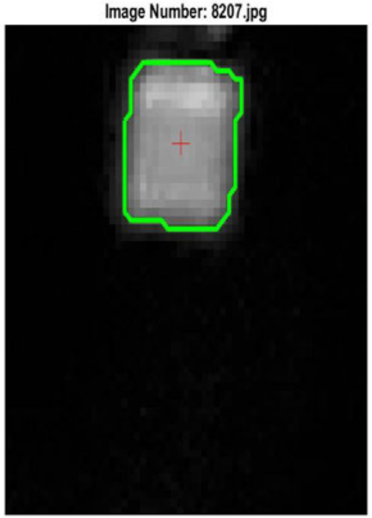
- Optical camera data processing has successfully detected mock CubeSats in both simulations and field data from 5-100m in all cases
- CubeSat detection operates well above requirements for given ideal conditions



100m



95m

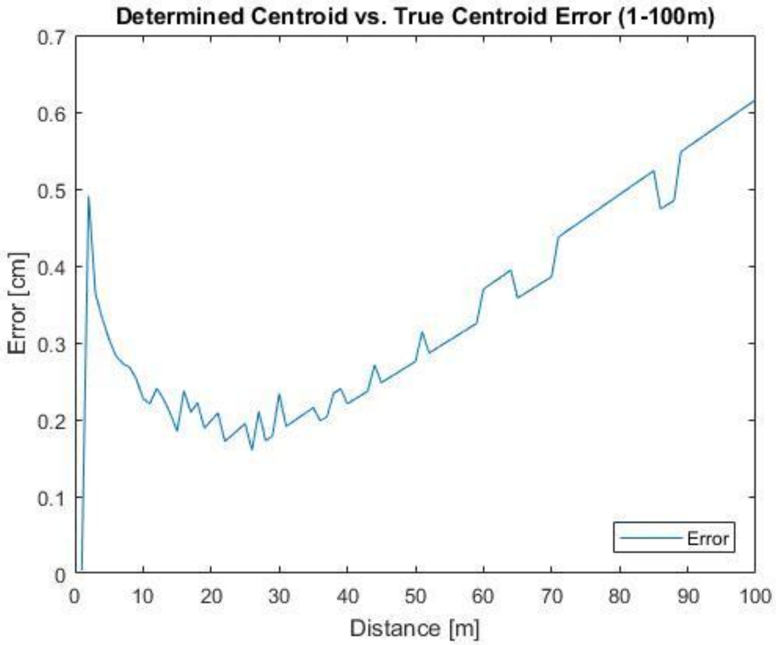


90m

Req.	Summary
DR 5.2	Software shall detect mock CubeSats within FOV at a distance of 3-100m

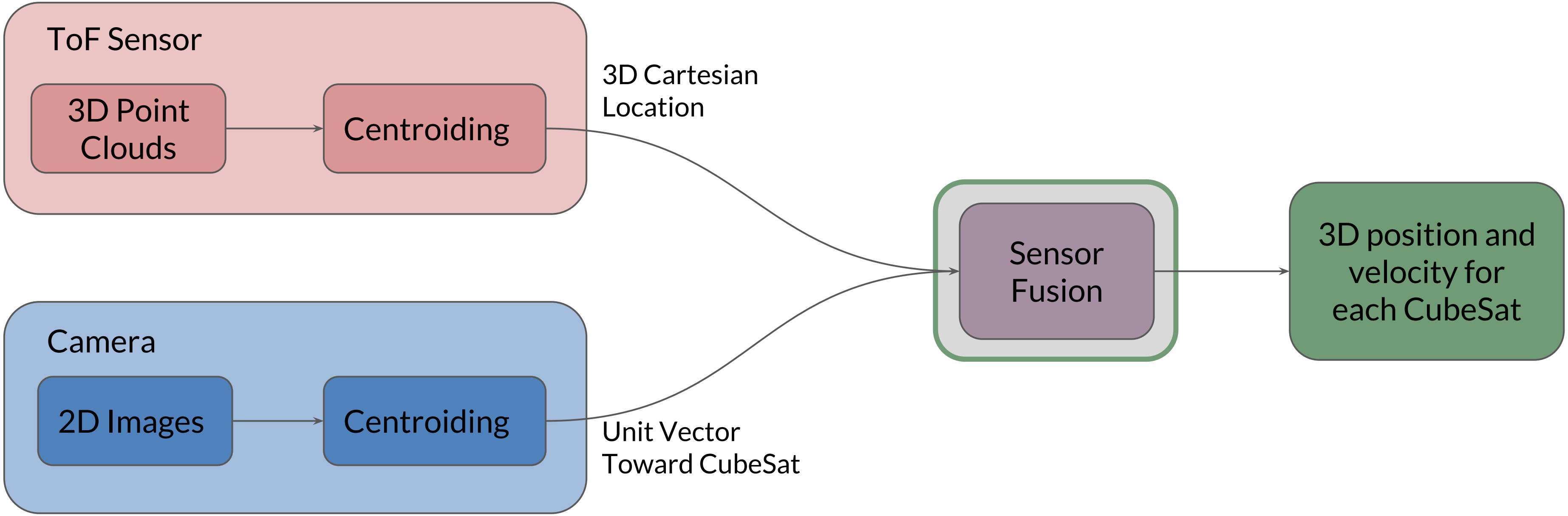
Optical Camera Ideal Simulation Accuracy

- Simulated data collected under ideal conditions
  - No blur, 1-D, linear velocity
- 2-D In-plane error at 100m < 1.0cm

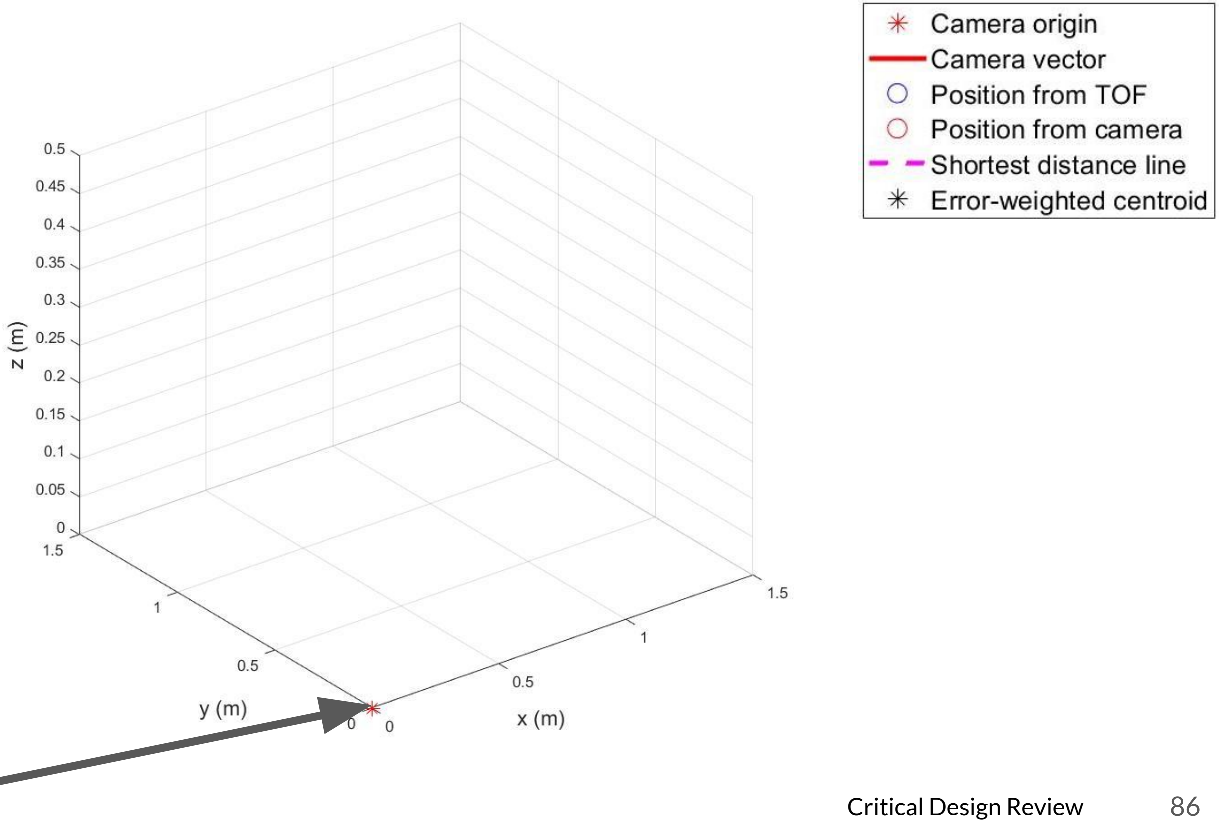


Req.	Summary
DR 5.2	Software shall detect mock CubeSats within FOV at a distance of 3-100m

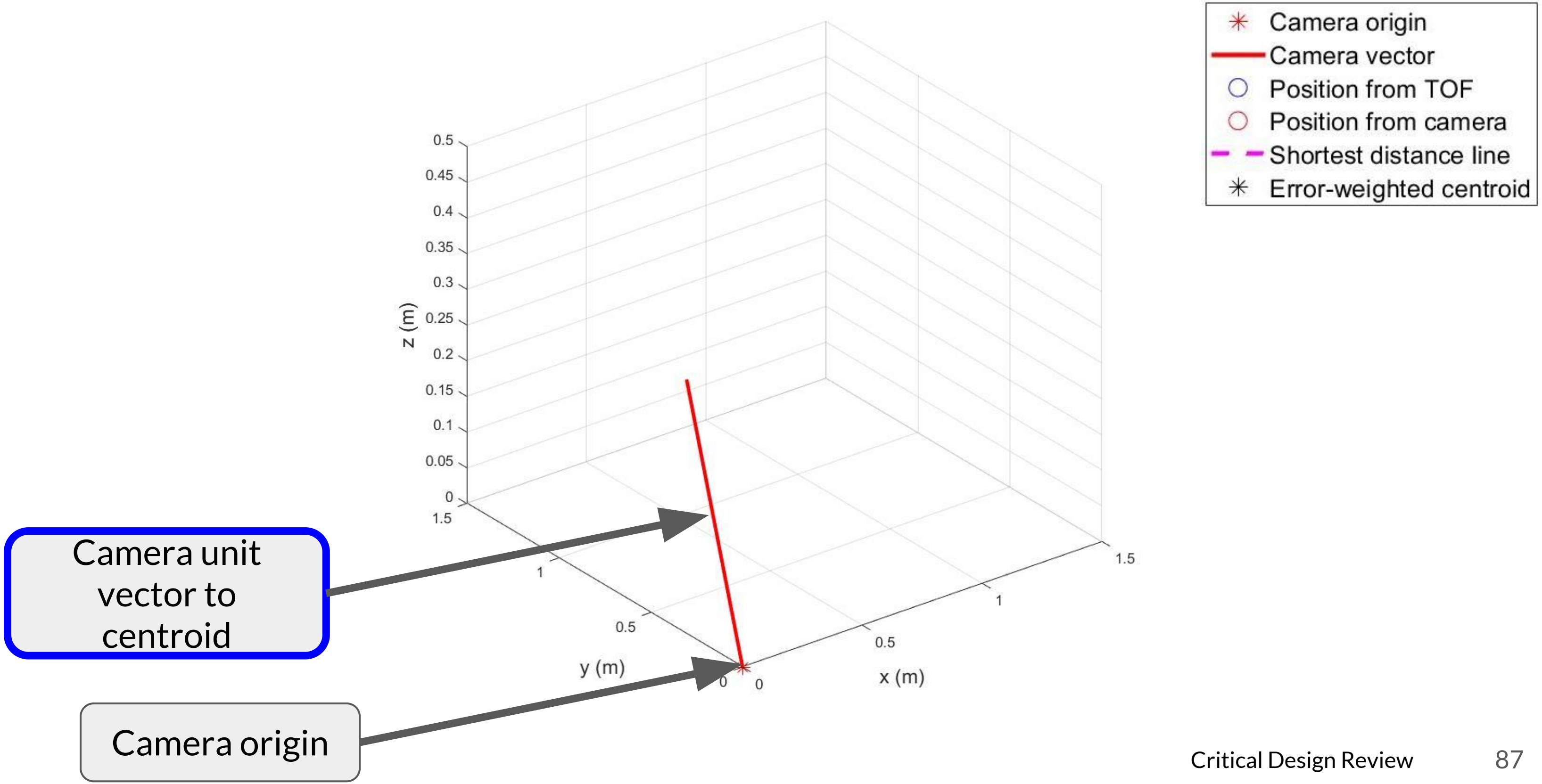
Producing Measurements from Sensor Data



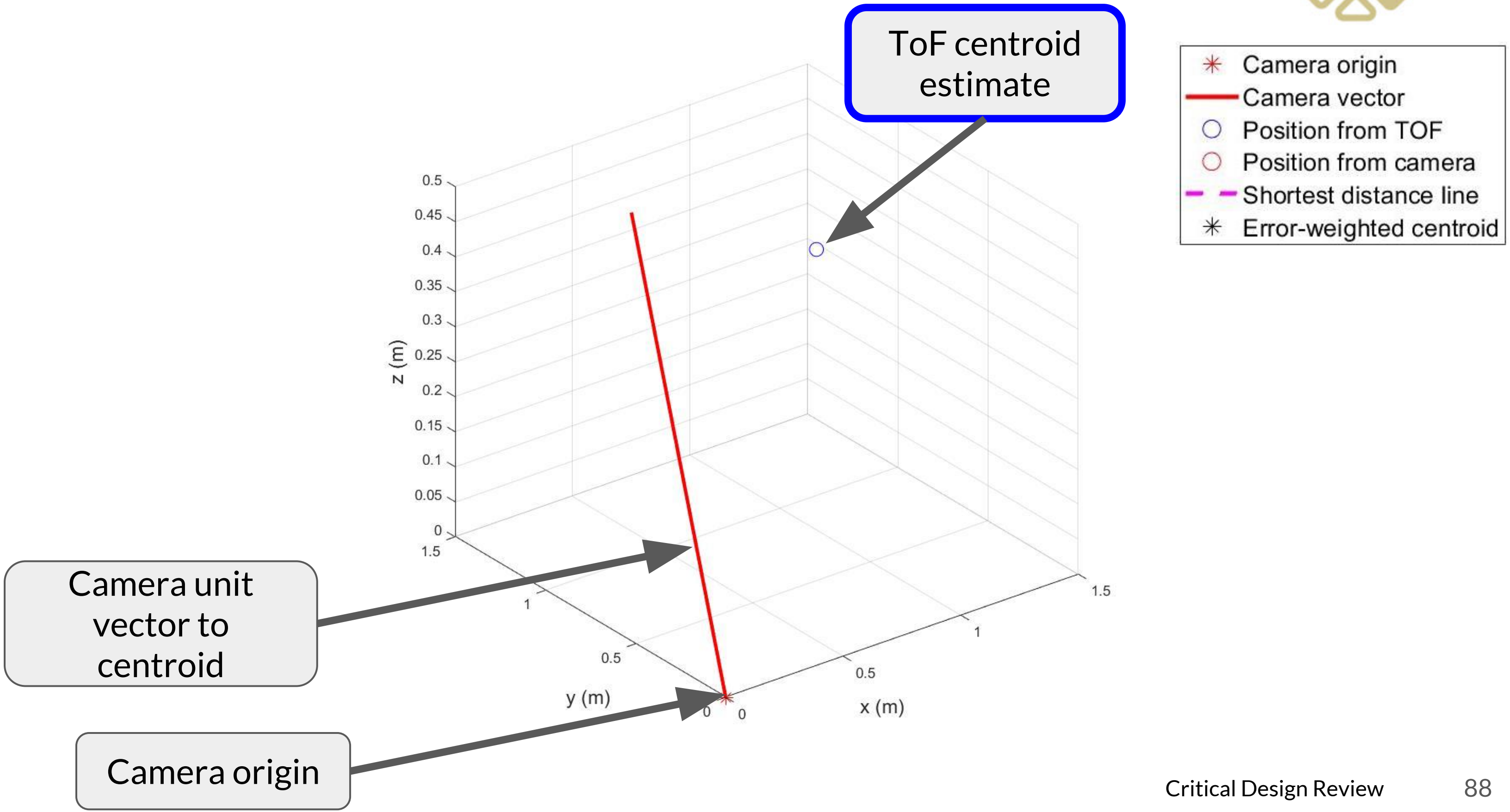
Sensor Fusion Method



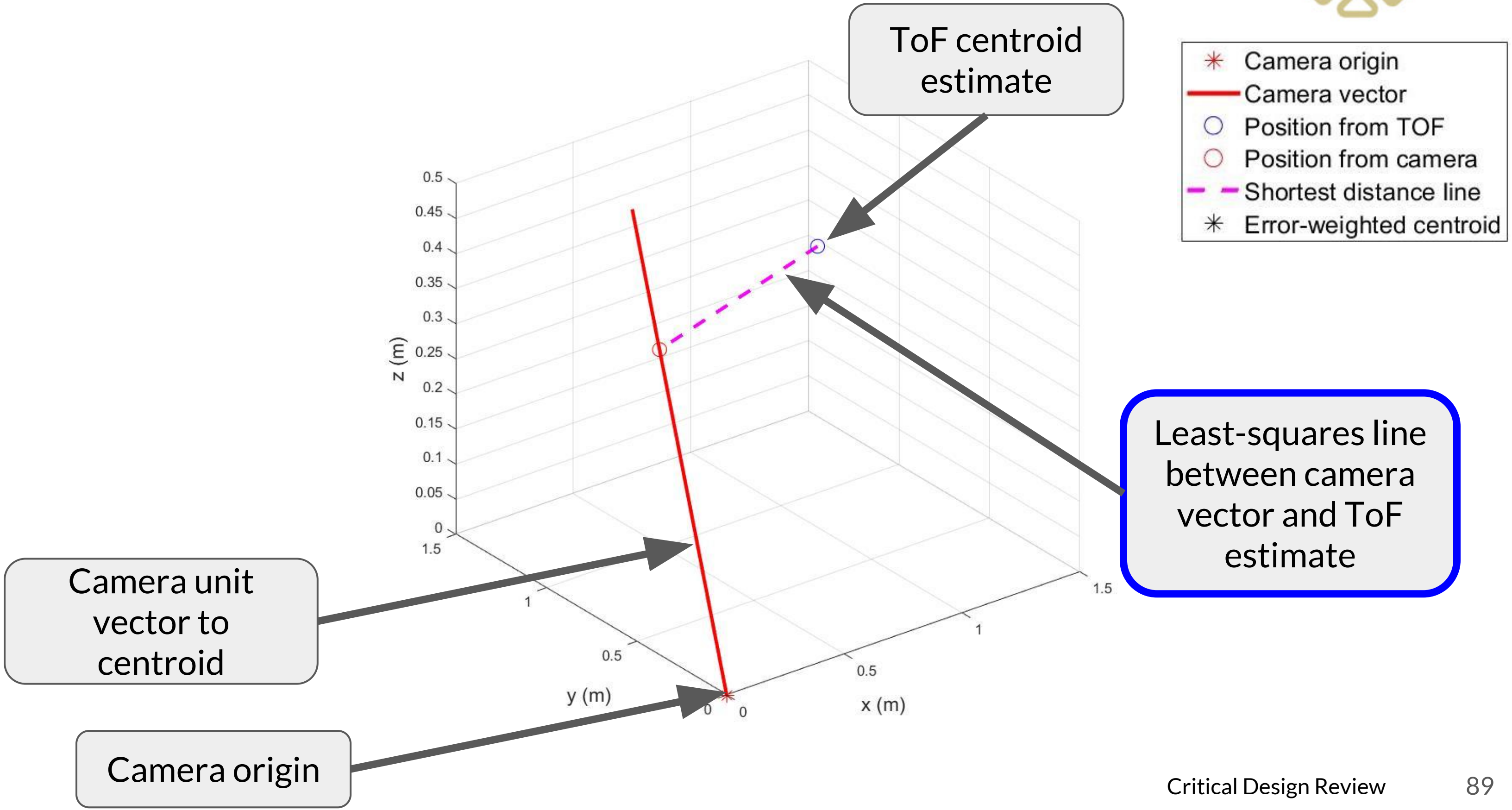
Sensor Fusion Method



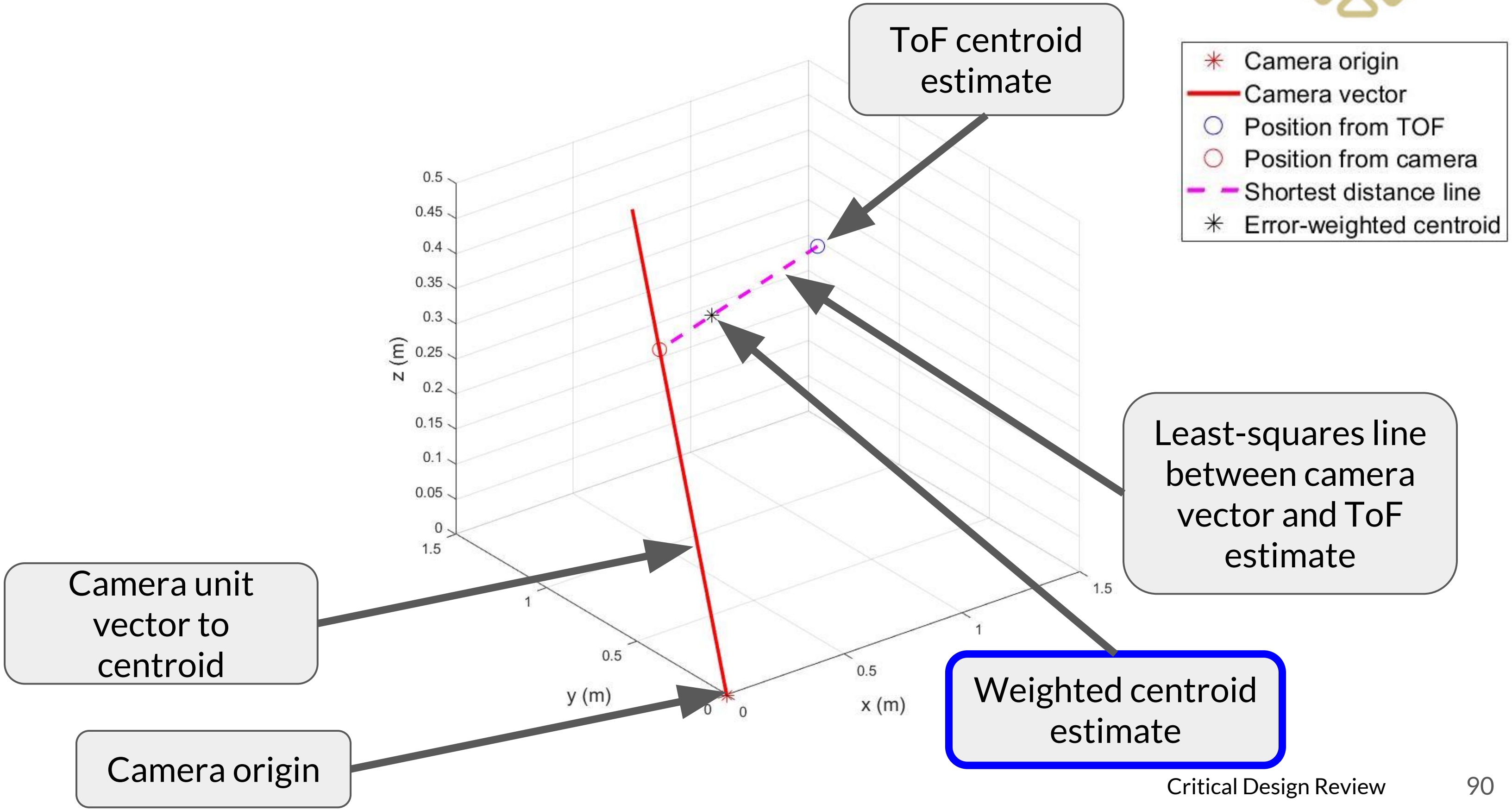
Sensor Fusion Method



Sensor Fusion Method

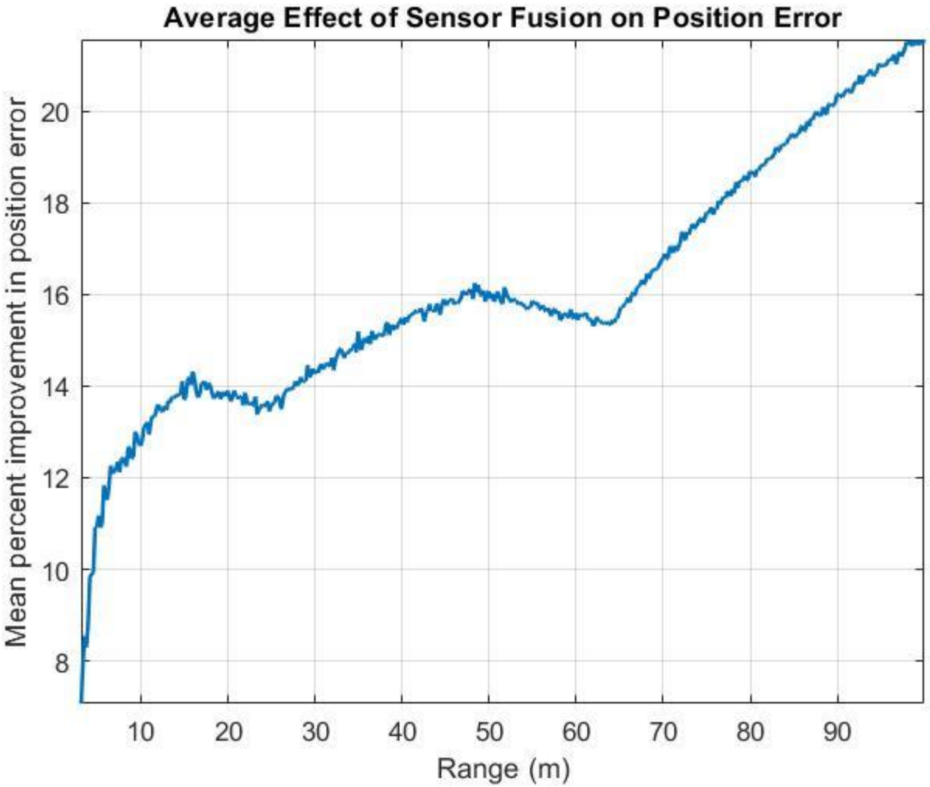


Sensor Fusion Method



Sensor Fusion Effectiveness

Distance (m)	100	50
Propagated ToF Mean Error (cm)	20.68	10.34
Sensor Fusion Mean Error (cm)	16.21	8.68
Error Requirement (cm)	1000	500



Avionics CPE Satisfaction

Data Storage and Processing Data

Our Software Benchmarks on our NUC

Process	Time*
Data import form ToF	6.54 Sec
Data import from Camera	11.65 Sec
ToF Centroiding	80 Sec
Image Processing	103.33 Sec
Camera Distortion	52.8 Sec
Sensor Fusion	0.1 Sec
Data Output to NR	52.08 Sec
Total	306.5 Sec = **5:06 Min**
Requirement	**15:00 Min**

*Support for these numbers in Backup

Electronic system time test on NUC

- **ToF** camera frame rate: **30 hz**
- **Camera** frame rate: **2 hz**
- *All runtimes produced from NUC testing*
- Data Output to NR is **500 KB over USB2.0**
- Data storage:
  - We require **40 GB < 500 GB** (NUC Storage)

Req.	Summary
DR 8.1	The electronics subsystem shall transmit results within 15 minutes of final mock CubeSat deployment.
DR 8.2	The system shall store all images, sensor data, and estimates within an onboard data storage device.

Risk Analysis

Pre-Mitigation Risk Matrix

	Likelihood of Occurrence					
Severity		Very Unlikely	Remote	Occasional	Probable	Frequent
	Catastrophic	SENS SN 2, STR HW 2	SW CMP 4, SW CMP 6, SW CMP 5			
	Significant	STR HW 3, TST MOD 4, SW CMP 3	AVI DEV 1, SENS SN 1, SENS TST 1, SENS TST 2, TST MOD 1, SW TST 1	AVI COMM 1, STR HW 1	SW CMP 1, TST MOD 2	
	Moderate	AVI PWR 1, AVI PWR 2, AVI PWR 3, TST 100M 2	TST MOD 5, TST 100M 1, SW CMP 2, TST MOD 3, AVI COMM 2	SENS SN 3		
	Minimal			AVI DEV 2	TST 100M 3	
	Insignificant					

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	Significant	STR HW 3, TST MOD 4, SW CMP 3	AVI DEV 1, SENS SN 1, SENS TST 1, SENS TST 2, TST MOD 1, SW TST 1	AVI COMM 1, STR HW 1	SW CMP 1, TST MOD 2	
	Moderate	AVI PWR 1, AVI PWR 2, AVI PWR 3, TST 100M 2	TST MOD 5, TST 100M 1, SW CMP 2, TST MOD 3, AVI COMM 2	SENS SN 3		
	Minimal			AVI DEV 2	TST 100M 3	
	Insignificant					

Risk Analysis

RISK ID	IF	THEN	ORIGINAL SEVERITY	ORIGINAL PROBABILITY	RISK SCORE	MITIGATION STRATEGIES	POST-MITIGATION SEVERITY	POST-MITIGATION PROBABILITY	POST-MITIGATION RISK SCORE
SW CMP 1	Software team encounters blocks during development.	Significant man hours invested to fix issues.	4	4	16	Extensive Architecture Simulation of sensors for unit testing	3	2	6
TST MOD 2	Test structure interferes with data measurement.	Modular test unable to produce usable data.	4	4	16	Use IR black paint to obscure test rig to TOF and optical sensor Use Stop motion and simulation to verify all requirements	1	3	3
AVI COMM 1	Arduino fails to remotely turn on NUC	NUC is never booted, mission entirely fails	4	3	12	Multiple methods of booting the NUC developed	3	2	6
STR HW 1	Competition for machine shop time prevents structural manufacturing.	VANTAGE structure is not produced.	4	3	12	PHYS water jet -> rapid manufacturing Manufacturing of simple rigs over break	2	1	2

Risk Analysis

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Pre-Mitigation Risk Matrix

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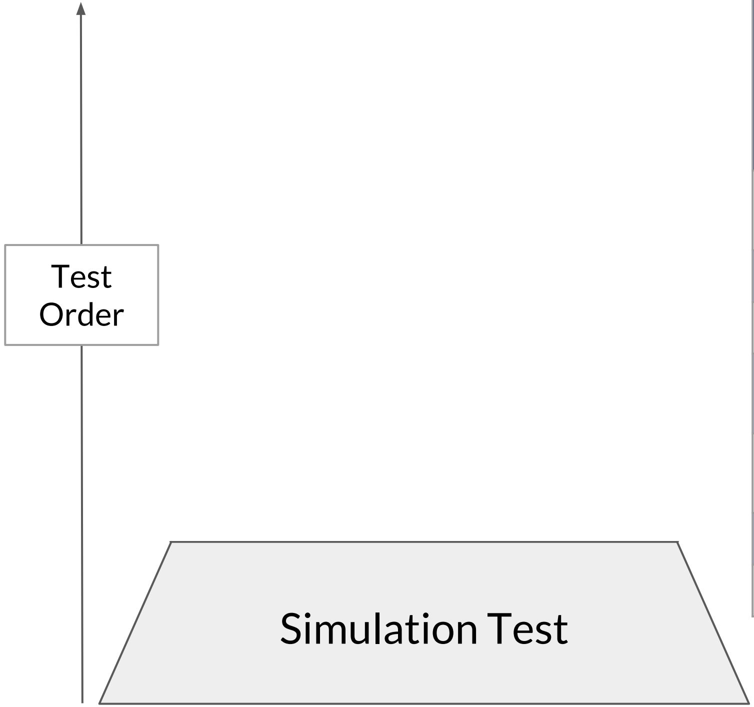
	Significant	STR HW 3, TST MOD 4, SW CMP 3	AVI DEV 1, SENS SN 1, SENS TST 1, SENS TST 2, TST MOD 1, SW TST 1	AVI COMM 1, STR HW 1	SW CMP 1, TST MOD 2	
	Moderate	AVI PWR 1, AVI PWR 2, AVI PWR 3, TST 100M 2	TST MOD 5, TST 100M 1, SW CMP 2, TST MOD 3, AVI COMM 2	SENS SN 3		
	Minimal			AVI DEV 2	TST 100M 3	
	Insignificant					

Post-Mitigation Risk Matrix

		Likelihood of Occurrence				
		Very Unlikely	Remote	Occasional	Probable	Frequent
Severity	Catastrophic	SW CMP 4				
	Significant	SENS TST 2				
	Moderate	SW CMP 6, SENS SN 3, SW TST 1, SENS SN 2	SW CMP 1, AVI COMM 1, AVI DEV 1			
	Minimal	STR HW 1, STR HW 2, STR HW 3, TST MOD 4, AVI PWR 1, AVI PWR 2, AVI PWR 3, TST 100M 2	SENS SN 1, SENS TST 1, TST MOD 1, TST MOD 5, TST 100M 1			
	Insignificant	SW CMP 5, AVI COMM 2, SW CMP 3	TST 100M 3, SW CMP 2, TST MOD 3	TST MOD 2, AVI DEV 2		

Verification and Validation

VANTAGE's Three Test Systems

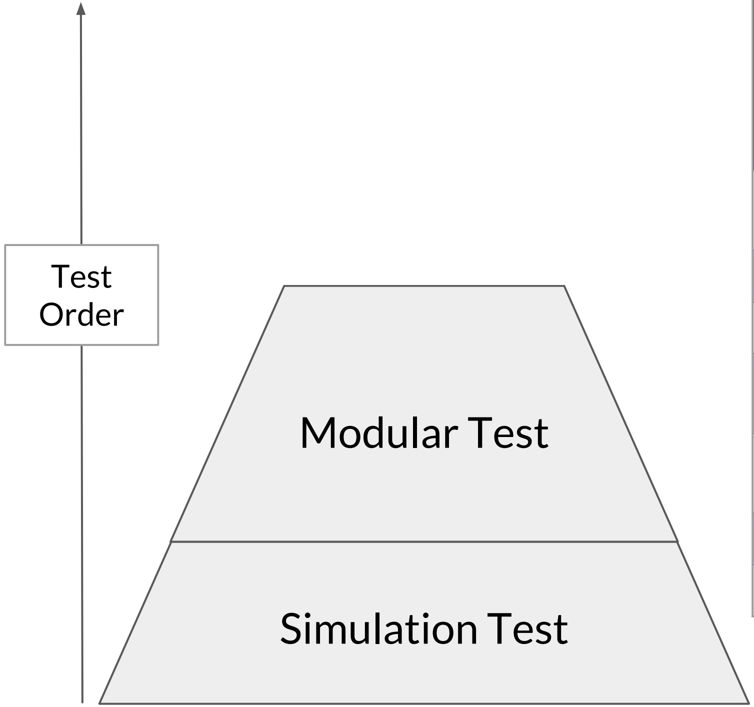


Functional Req.	Summary	Simulation Test	Modular Test*	100m Test**
FR.1	Images of Mock CubeSats between 3 and 100 m			
FR.2	Receive and interpret commands	✓		
FR.3	Accept NanoRacks DC power			
FR.5	Detect and track Mock CubeSats between 3 and 100m	✓		
FR.6	Estimate position and velocity vector of Mock CubeSats	✓		
FR.7	Off nominal deployment cases	✓		
FR.8	Reporting data back to user	✓		

*Real world sensor data produced

**Real world sensor data produced + beginning to end system verification

VANTAGE's Three Test Systems



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FR.8	Reporting data back to user	✓	✓	

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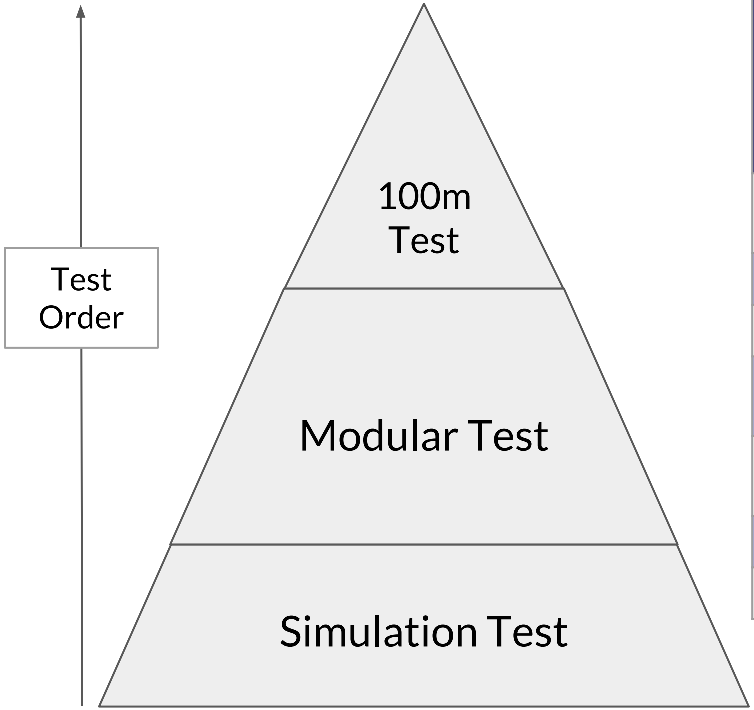
VANTAGE’s Three Test Systems



Functional Req.	Summary	Simulation Test	Modular Test*	100m Test**
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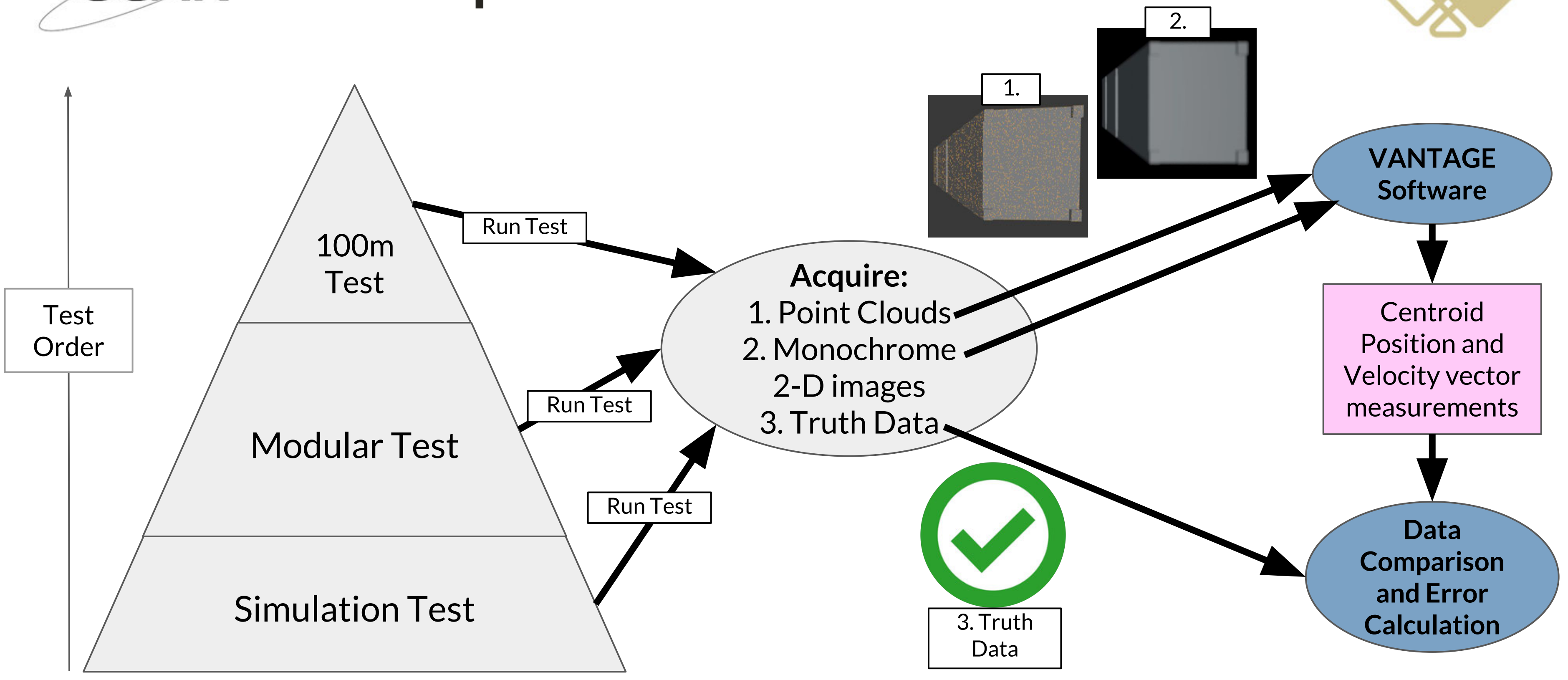
FR.3	Accept NanoRacks DC power			✓
FR.5	Detect and track Mock CubeSats between 3 and 100m	✓	✓	✓
FR.6	Estimate position and velocity vector of Mock CubeSats	✓	✓	✓
FR.7	Off nominal deployment cases	✓	✓	
FR.8	Reporting data back to user	✓	✓	✓

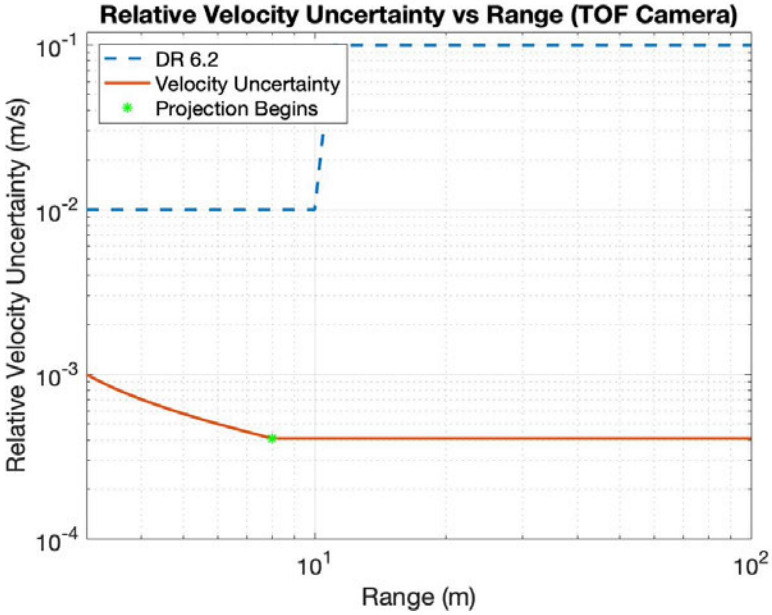
*Real world sensor data produced
**Real world sensor data produced + beginning to end system verification

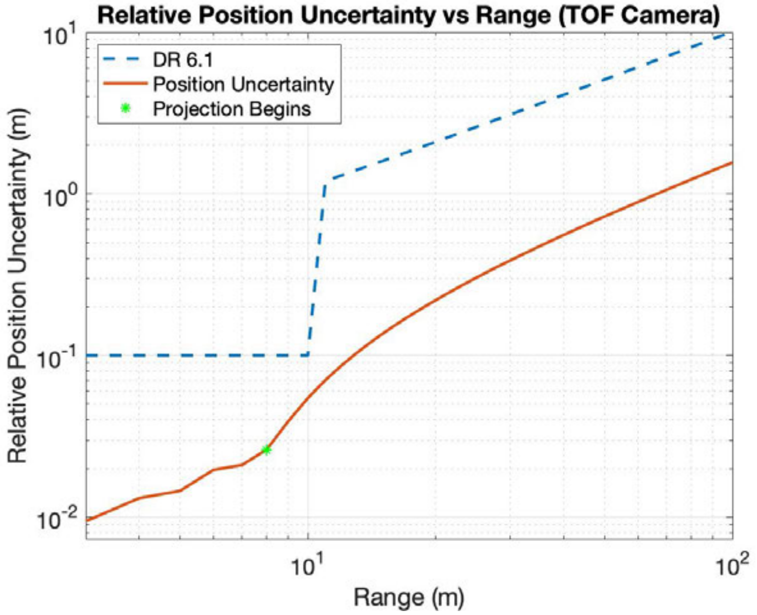
Requirement Verification Plan



Requirement Validation Plan

- After data comparison and error calculation, plots similar to the following are generated to verify that the VANTAGE system produces measurements which meet or exceed requirements





Test System Use Over Course of Development

Development Phase

Software Development

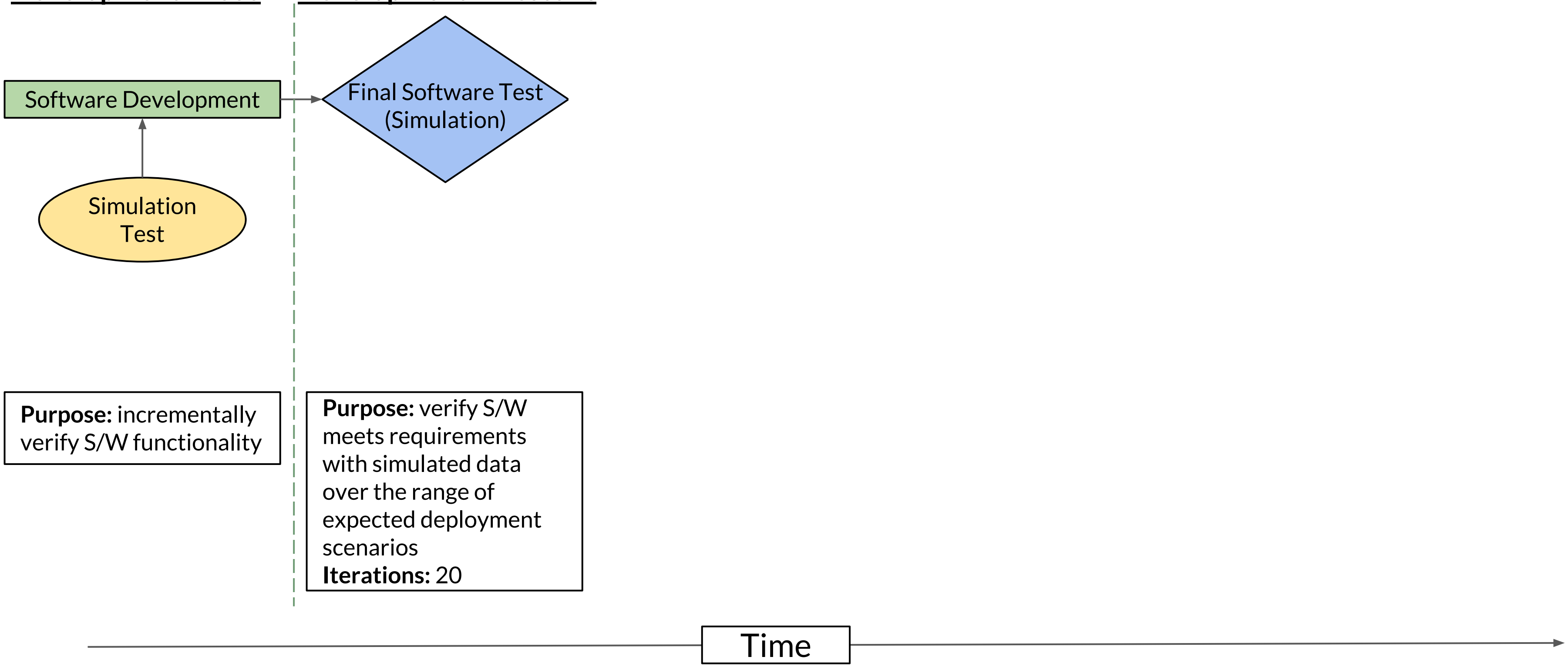
Simulation Test

Purpose: incrementally verify S/W functionality

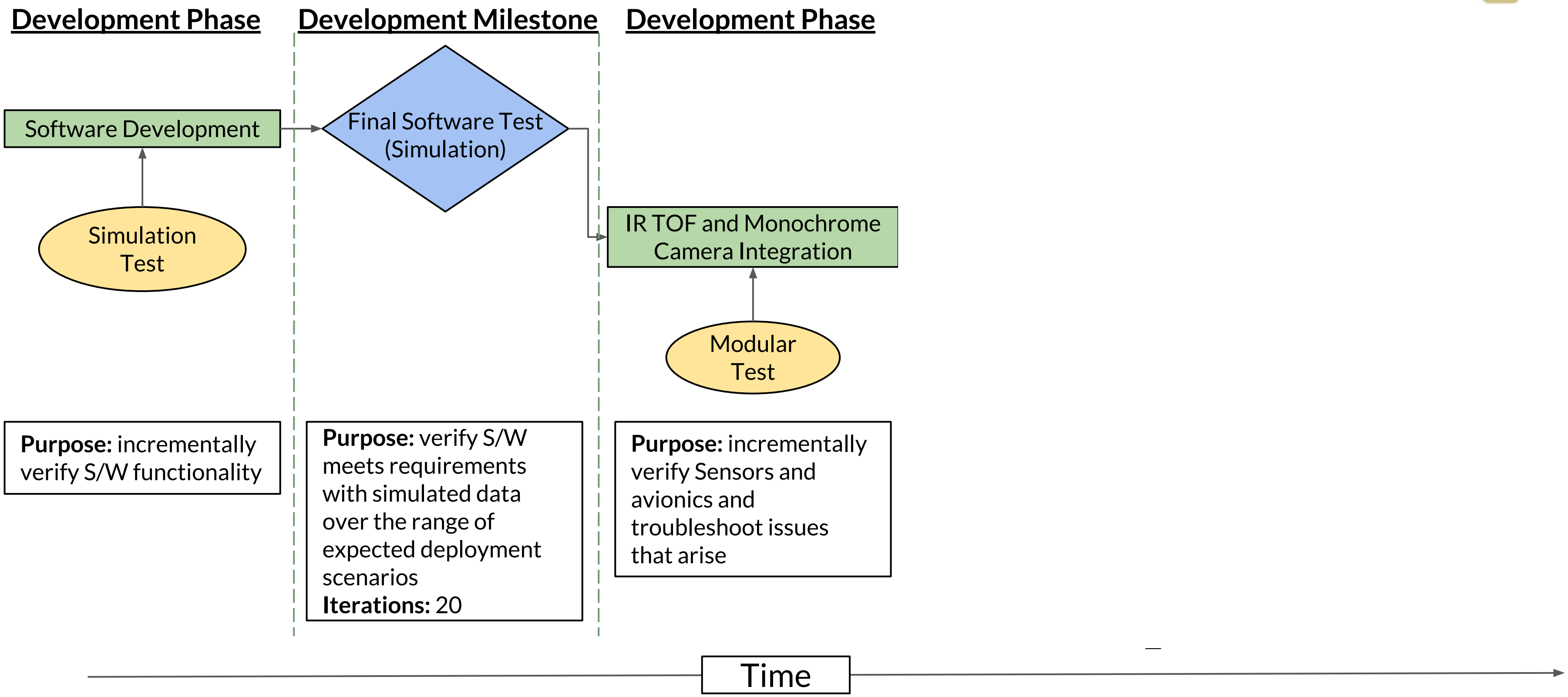
Time

Test System Use Over Course of Development

Development Phase | **Development Milestone**



Test System Use Over Course of Development



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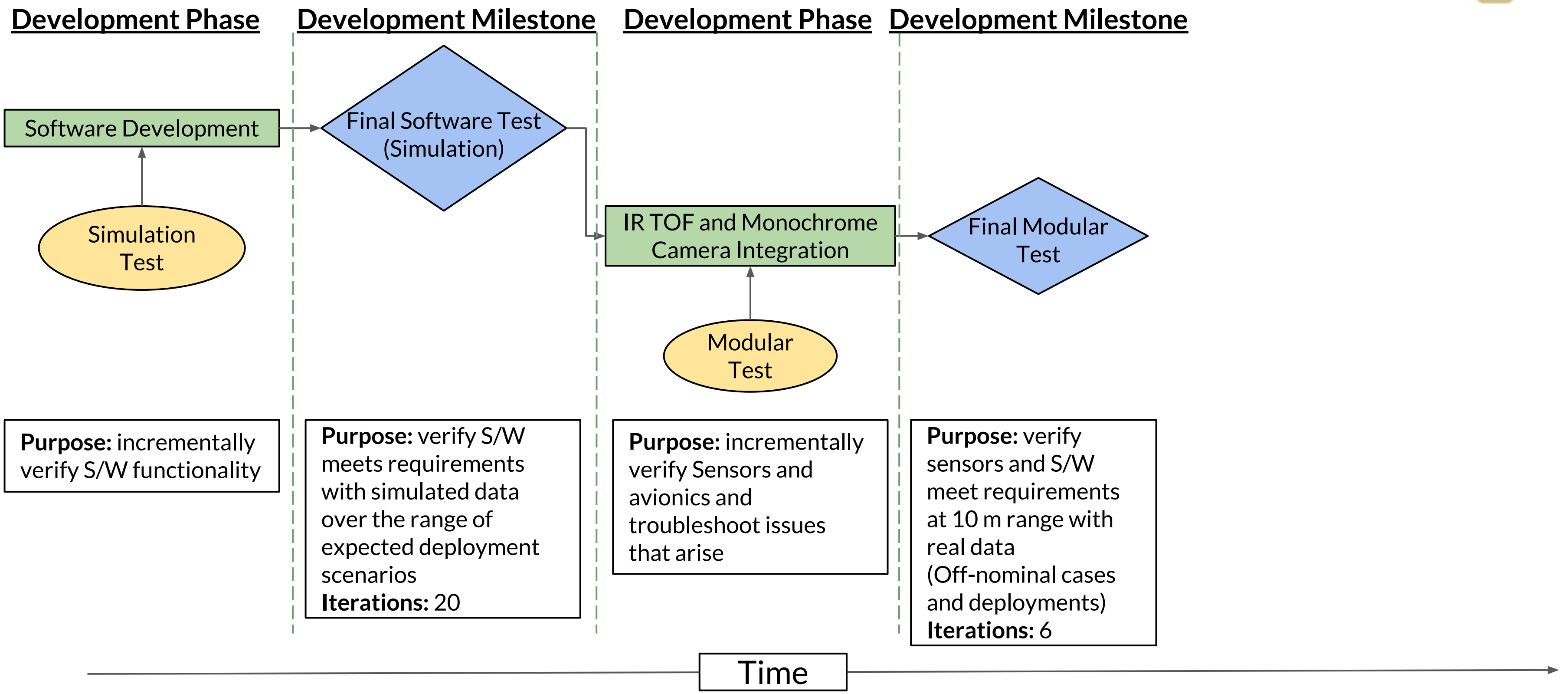
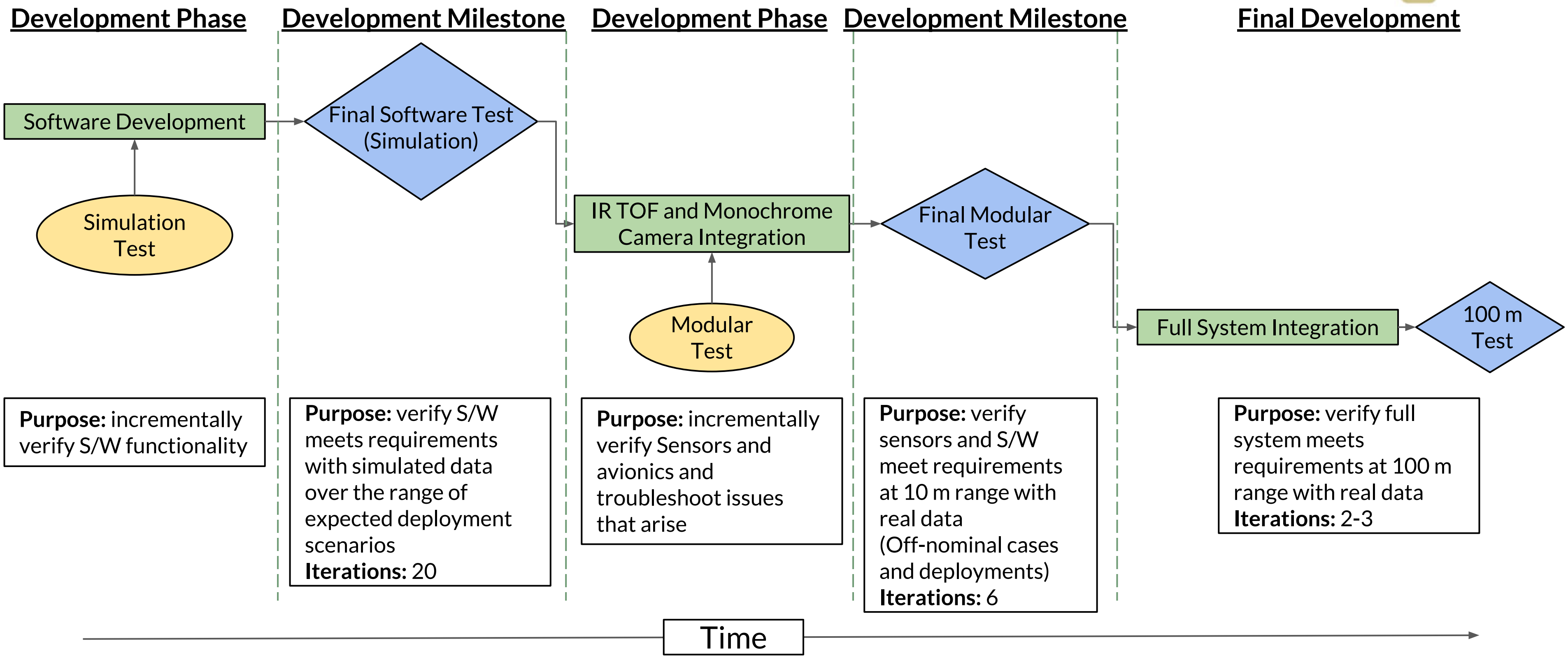


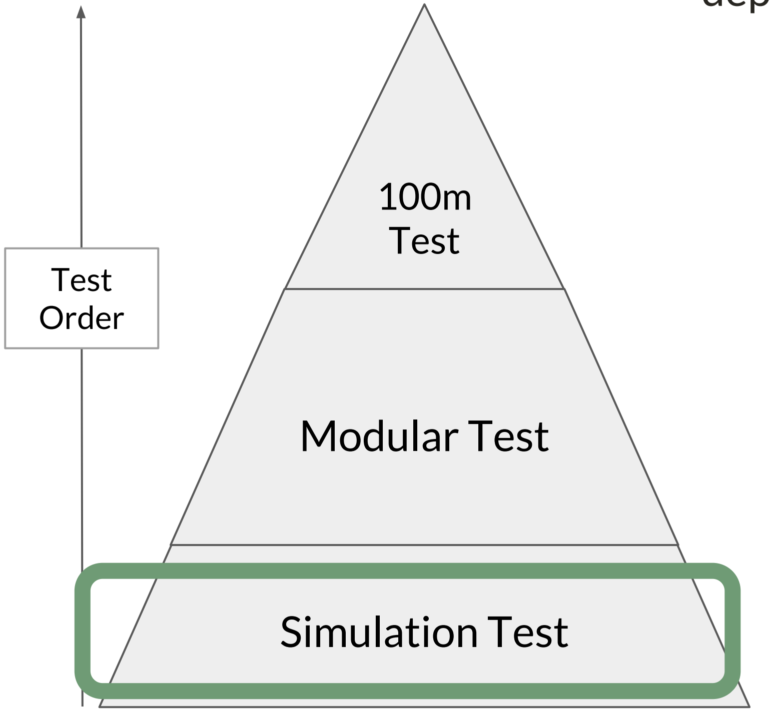
Test System Use Over Course of Development



VANTAGE Simulation

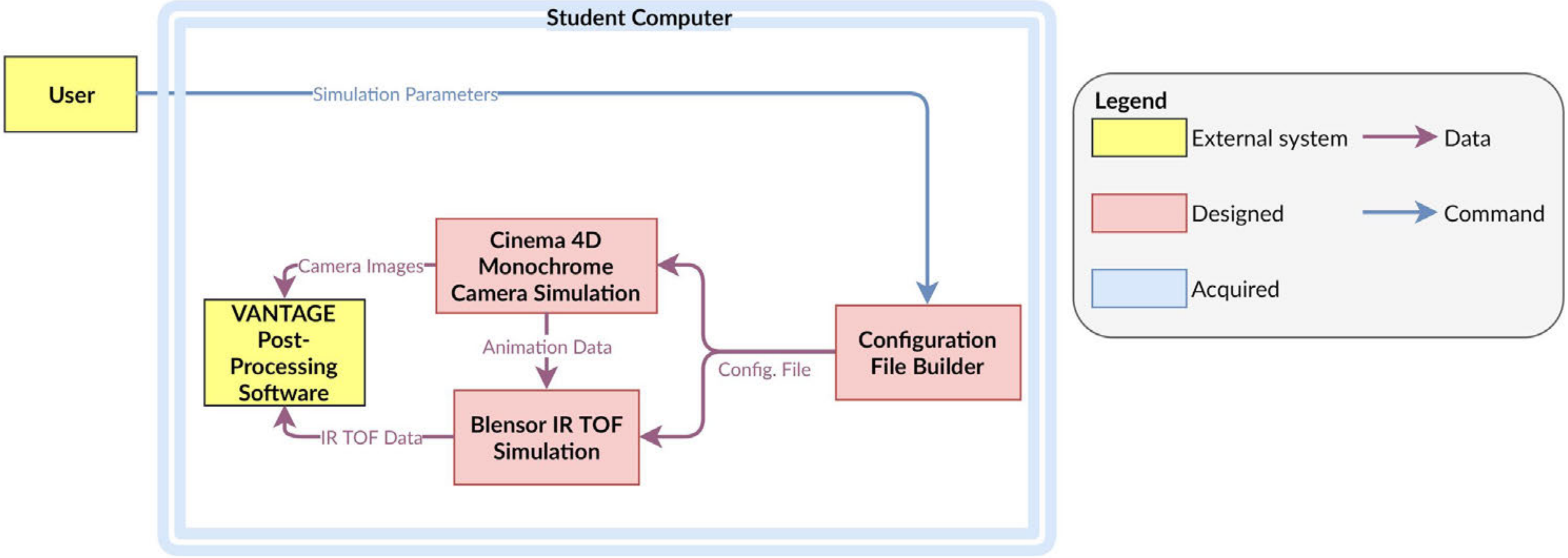
Simulation Overview

- A simulated test of VANTAGE's software system in all required deployment scenarios in a virtual environment

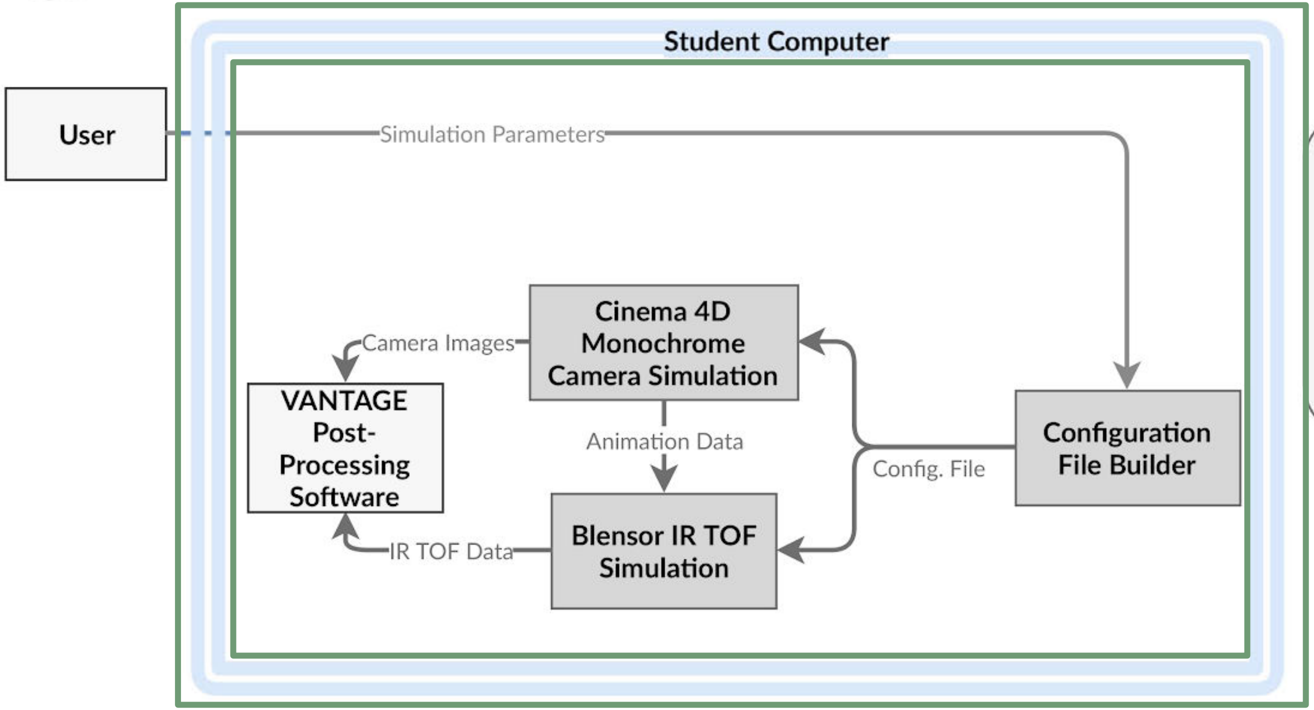


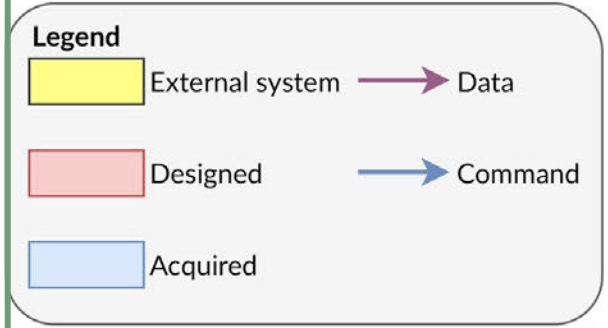
Relevant FR's: FR.5, FR.6, FR.7	
Relevant DR's	Summary
DR.2.2	Interpret deployment manifest
DR.5.2	Mock cubesat detection
DR.6.1 DR.6.2	Position vector and velocity vector measurements are within error bounds
DR.7.2 DR.7.3	Off-nominal ejection times and velocities
DR.8.1	Report data back to the user

Simulation FBD

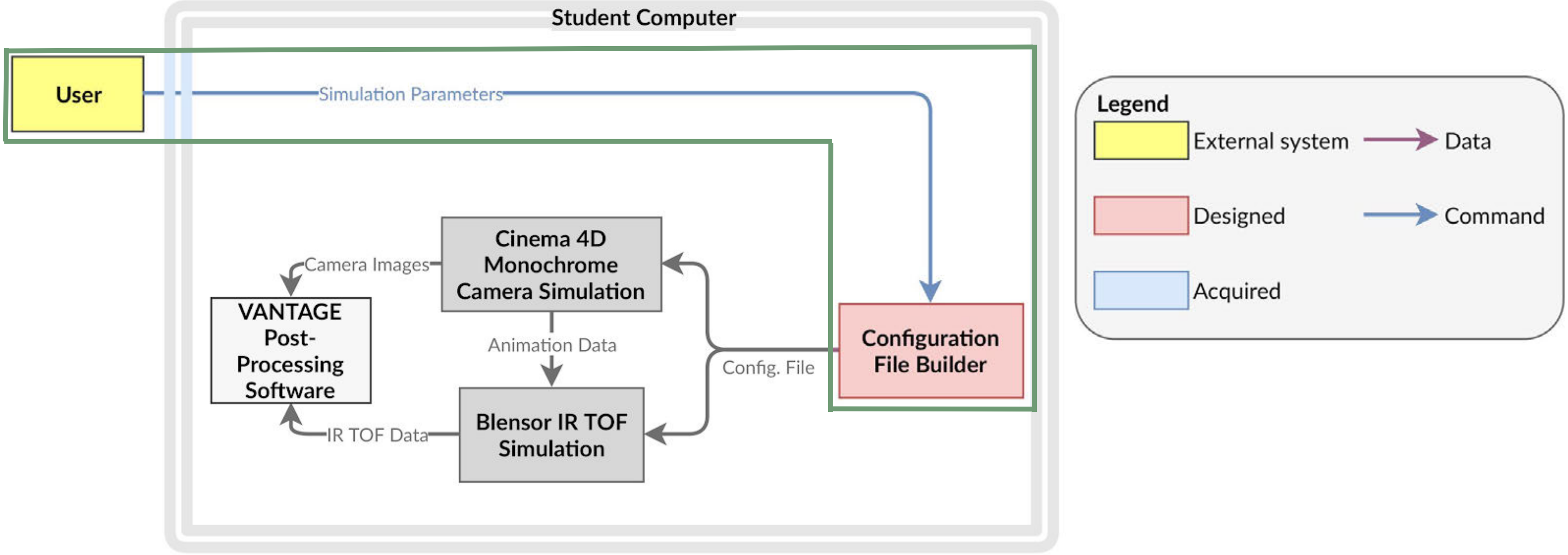


Simulation FBD

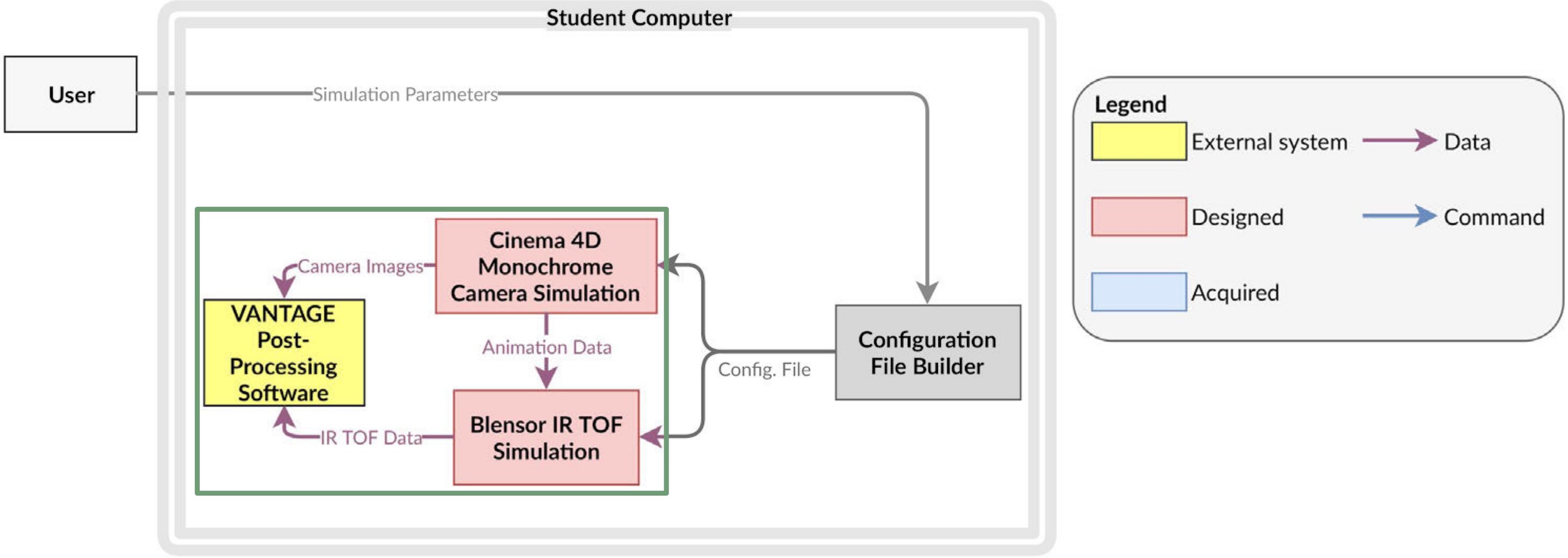




Simulation FBD



Simulation FBD



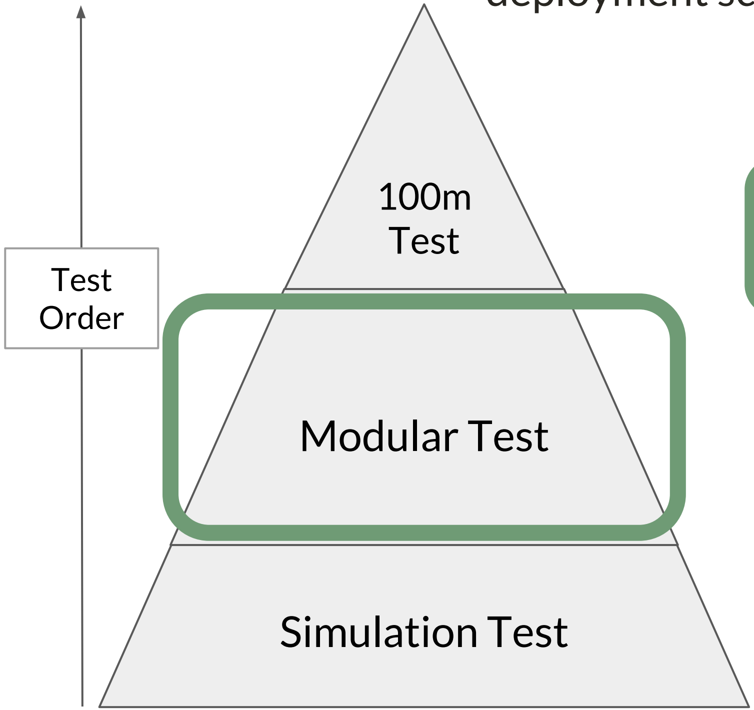
Simulation Overview

Necessary Capability/ Measurement	Software Used	Simulation Capability	Relevant Requirements
Truth Data **(Position & Velocity)**	Inputs to the simulation	Absolute accuracy	**DR.6.1:** Position Accuracy (**10 cm** for 3-10 10m ,10% of range to 100 m). **DR.6.2:** Velocity Accuracy (**1 cm/s** to 10 m , 10cm/s to 100m)
Test Data **(Position & Velocity)**	VANTAGE Post-Processing Software (**Unit Under Test**)	N/A	**DR.6.1** & **DR.6.2**
Various Deployment Scenarios	Cinema 4D/Blensor	Capable of simulating all deployment scenarios	**FR.5:** Mount up to **6 1U to 2 3U** Mock CubeSats
Mock CubeSat Motion	Cinema 4D	Capable of simulating motion	**FR.6, FR.7:** Mock Cubesats move with velocities between **0 and 3 [m/s]**.

Modular Test System

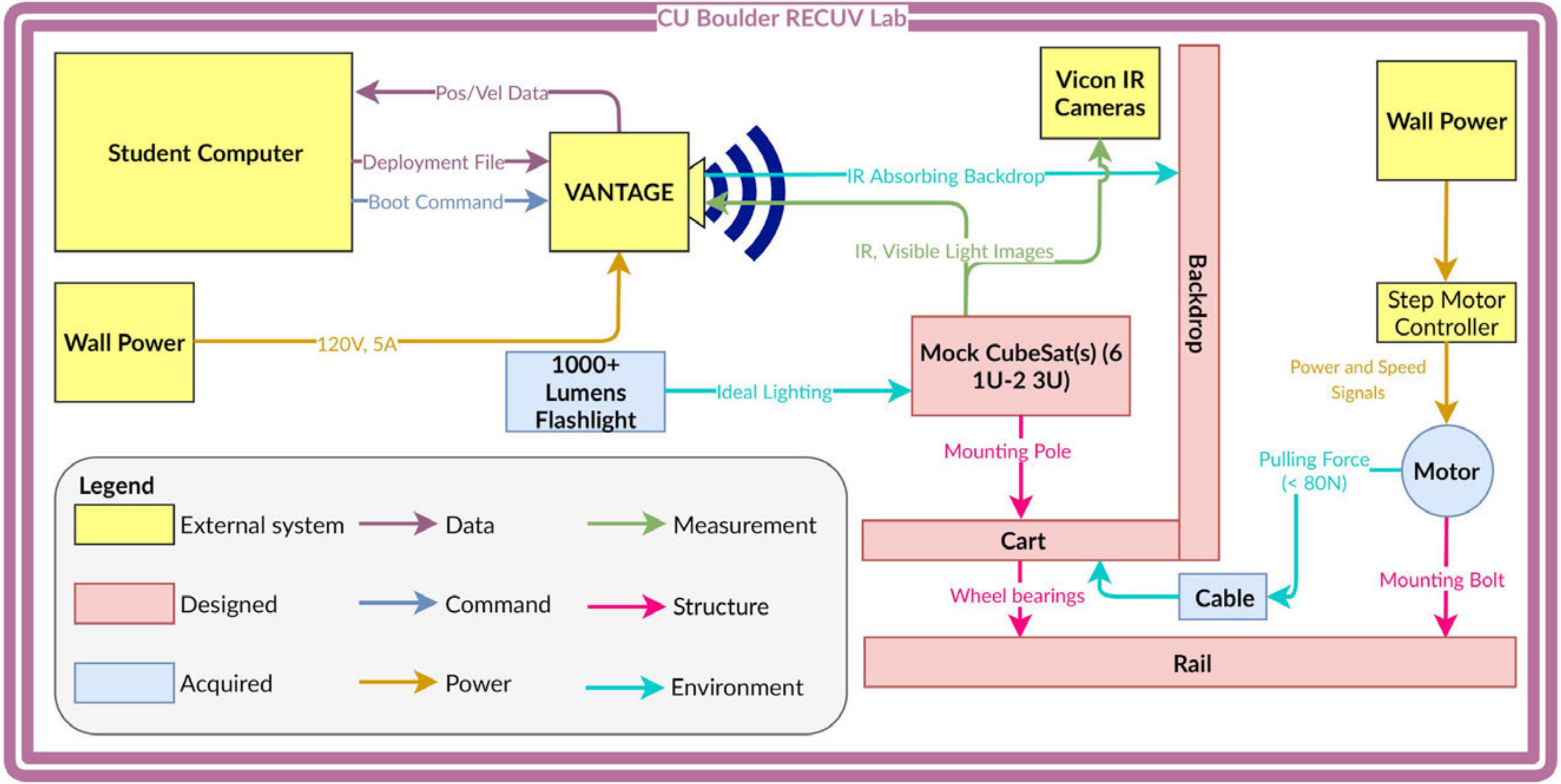
Modular Test Overview

- A 10 m test of VANTAGE's sensor and software systems in all required deployment scenarios in a ground based deployment simulated environment

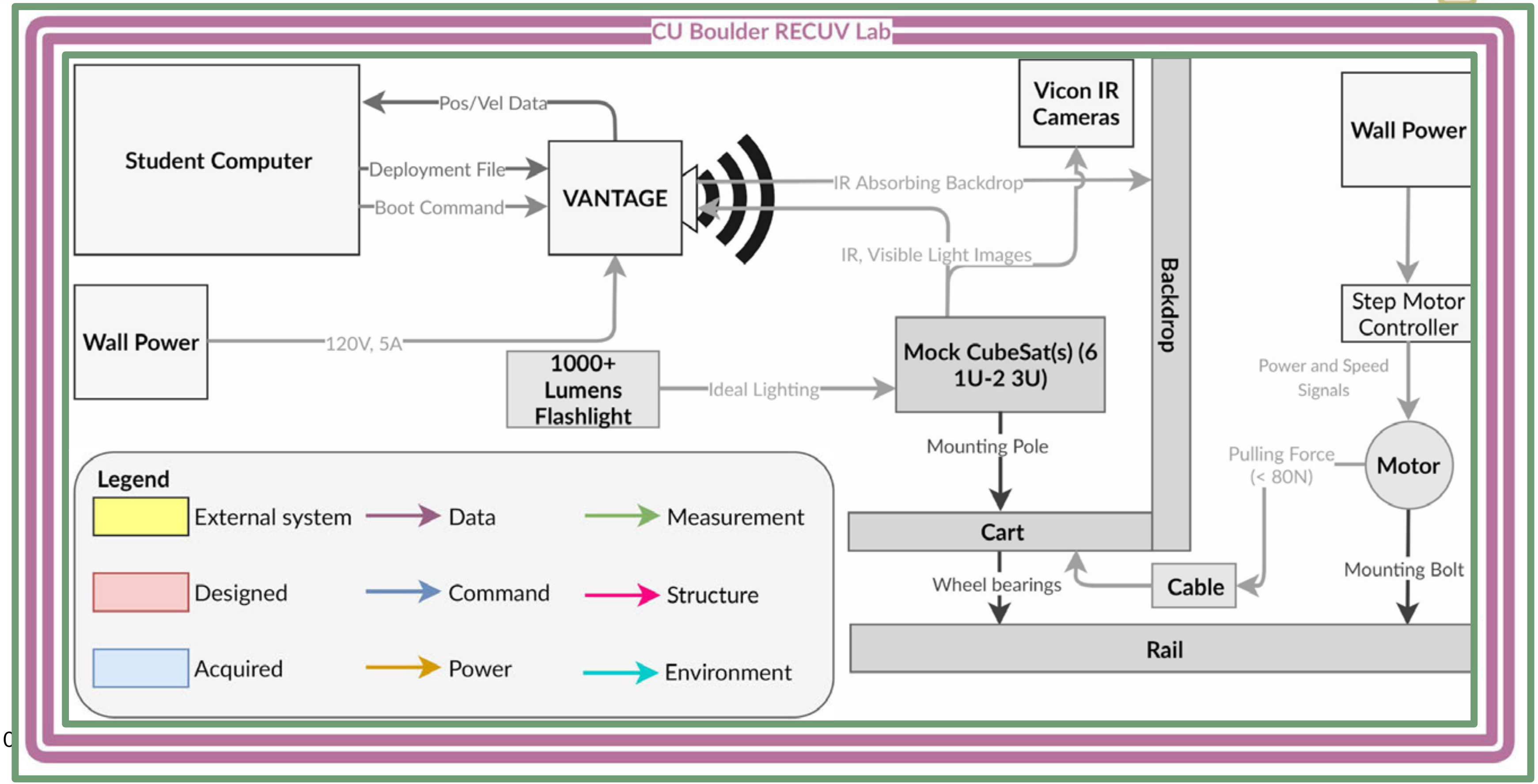


Relevant FR's: FR.1, FR.5, FR.6, FR.7	
Relevant DR's	**Summary**
DR.1.1 DR.1.3 DR.1.4	Camera system functionality and single infocus image return
DR.2.2	Interpret deployment manifest
DR.5.2	Mock cubesat detection
DR.6.1 DR.6.2	Position vector and velocity vector measurements are within error bounds
DR.7.2 DR.7.3	Off-nominal ejection times and velocities
DR.8.1	Report data back to the user

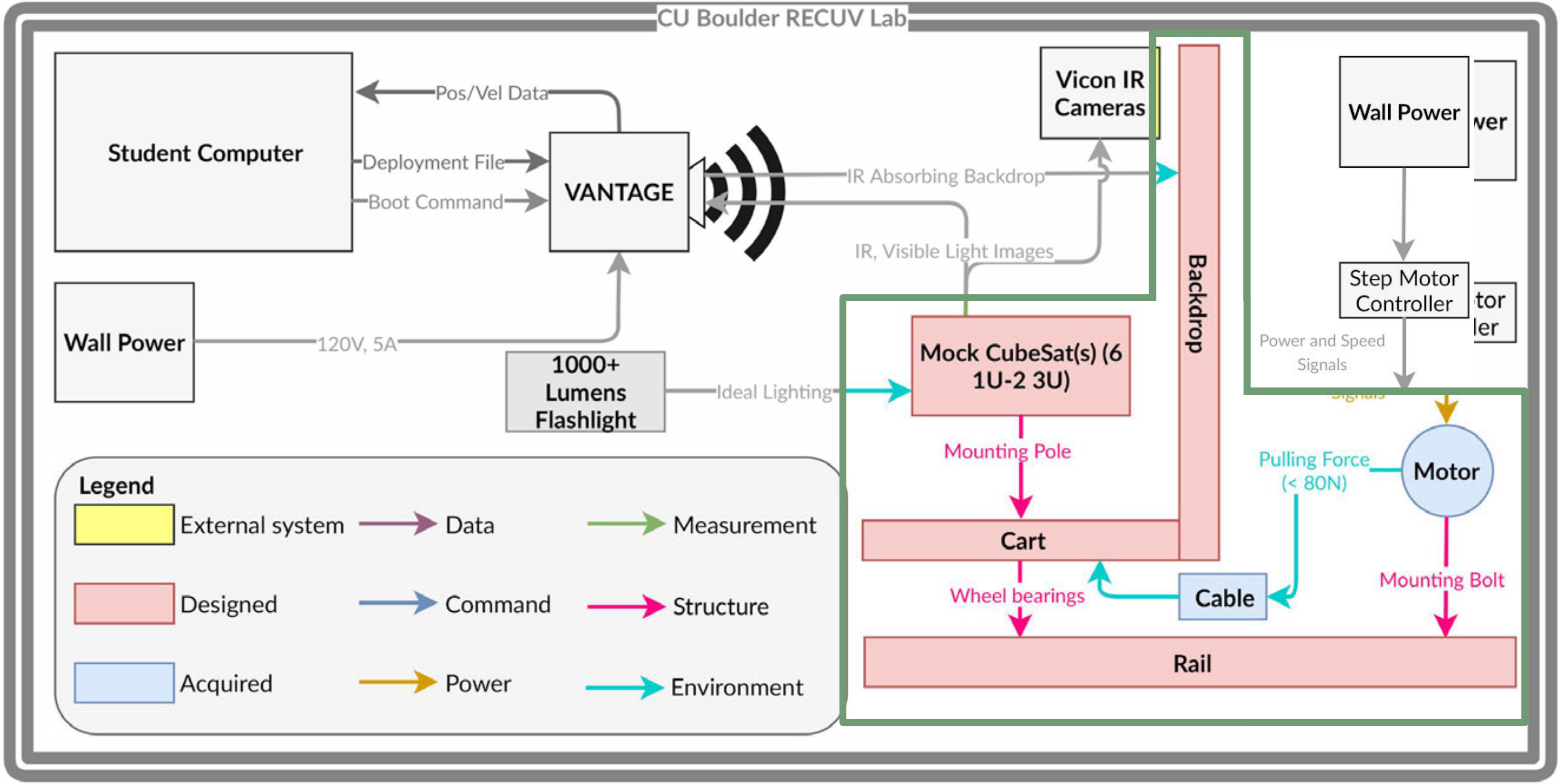
Modular Test FBD



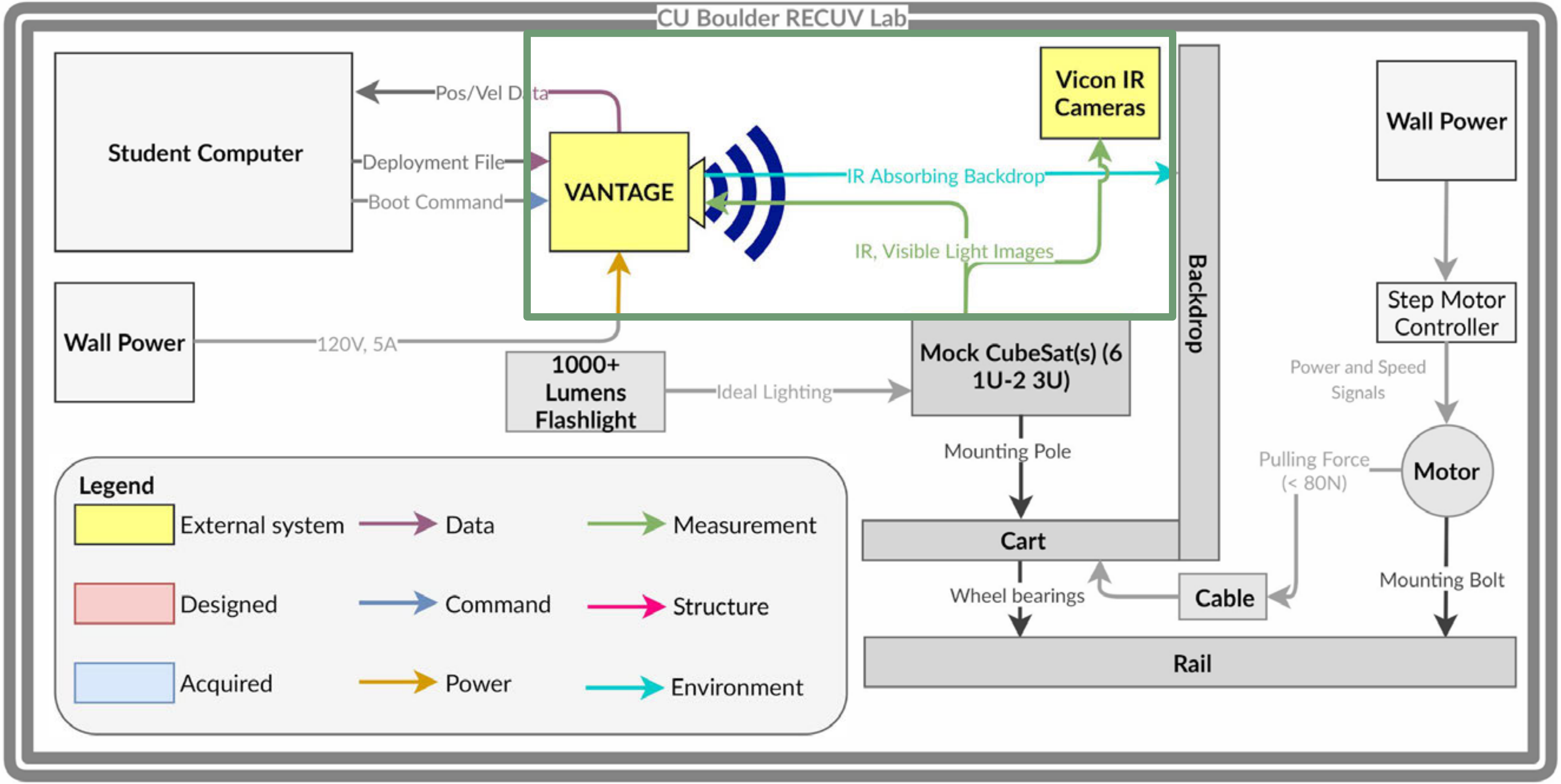
Modular Test FBD



Modular Test FBD



Modular Test FBD



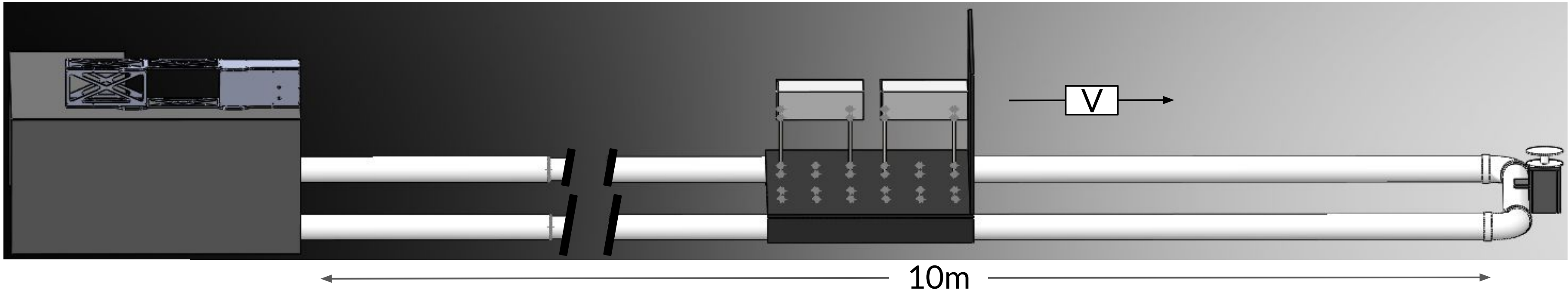
Modular Test Overview

Necessary Capability/ Measurement	Hardware Used	Hardware Capability	Relevant Requirements
Truth Data **(Position & Velocity)**	Vicon System	Position Error of **0.0775 mm** at **100 Hz**	**DR.6.1:** Position Accuracy (**10 cm** for 3-10 10m ,10% of range to 100 m).
		Velocity Error of **0.0775 mm/s**	**DR.6.2:** Velocity Accuracy (**1 cm/s** to 10 m , 10cm/s to 100m)
Test Data **(Position & Velocity)**	TOF & Optical Camera (**Unit Under Test**)	N/A	**DR.6.1** & **DR.6.2**
Imaging Targets	Mock CubeSat Models	Simulates the appearance of a CubeSat	**FR.1: Images** of Mock CubeSats
Various Deployment Scenarios	Mock CubeSat Cart	Capable of mounting all deployment scenarios	**FR.5:** Mount up to **6 1U to 2 3U** Mock CubeSats
Mock CubeSat Motion	Nema 34 Step Motor	Capable of the required torque and rpm to produce this motion.	**FR.6, FR.7:** Mock Cubesats move with velocities between **0 and 3 [m/s]**.

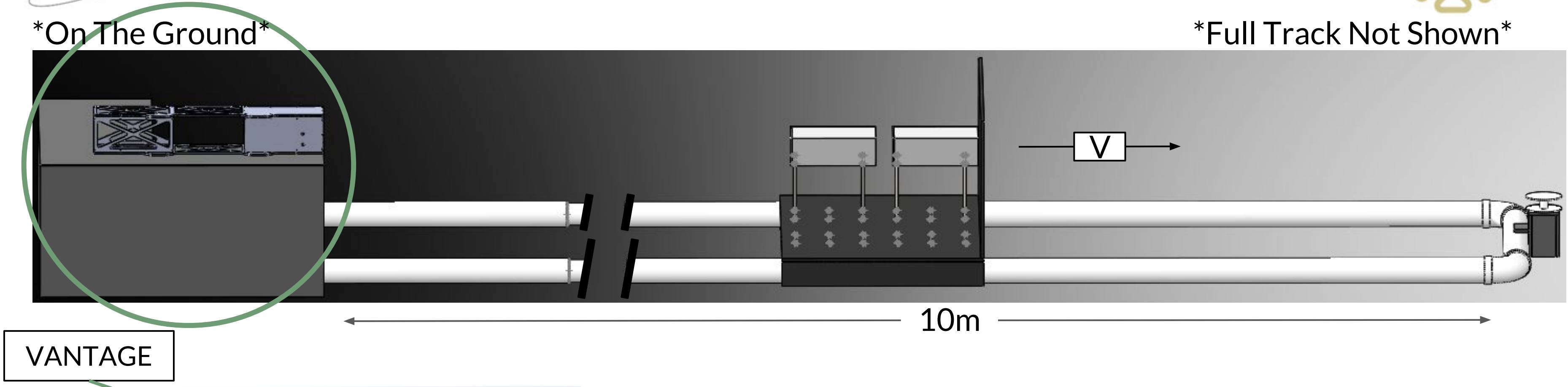
Modular Test Setup

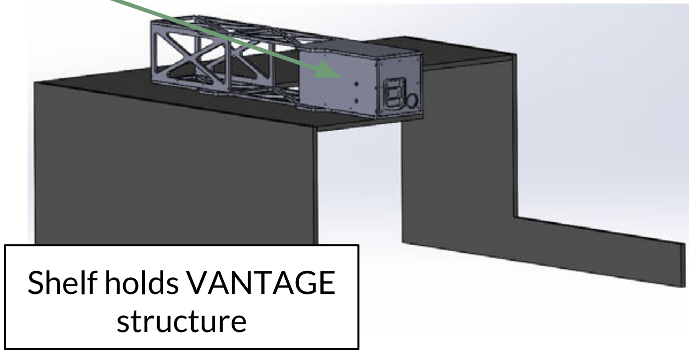
On The Ground

Full Track Not Shown



Modular Test Setup

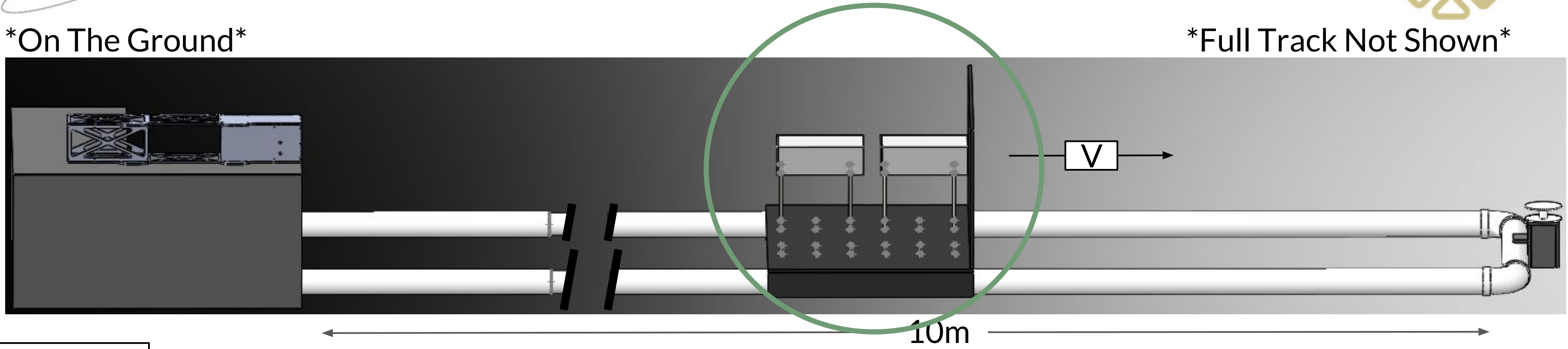




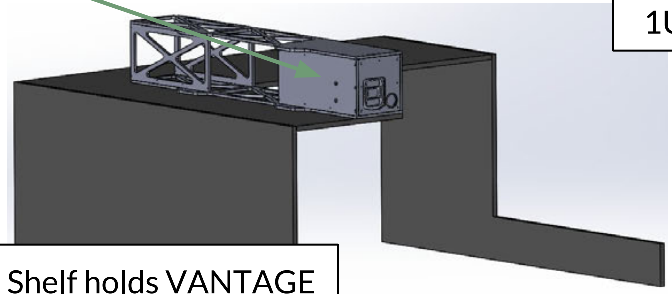
Modular Test Setup

On The Ground

Full Track Not Shown

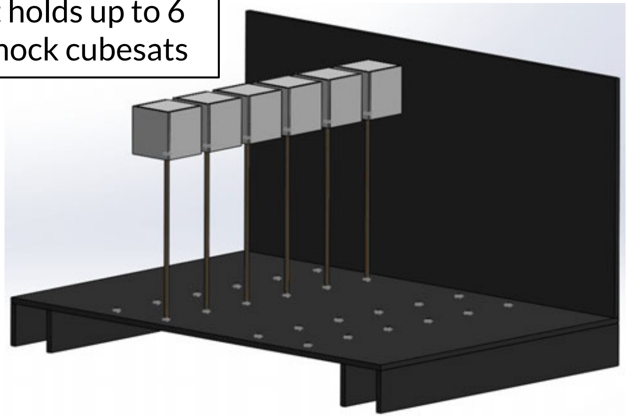


VANTAGE



Shelf holds VANTAGE structure

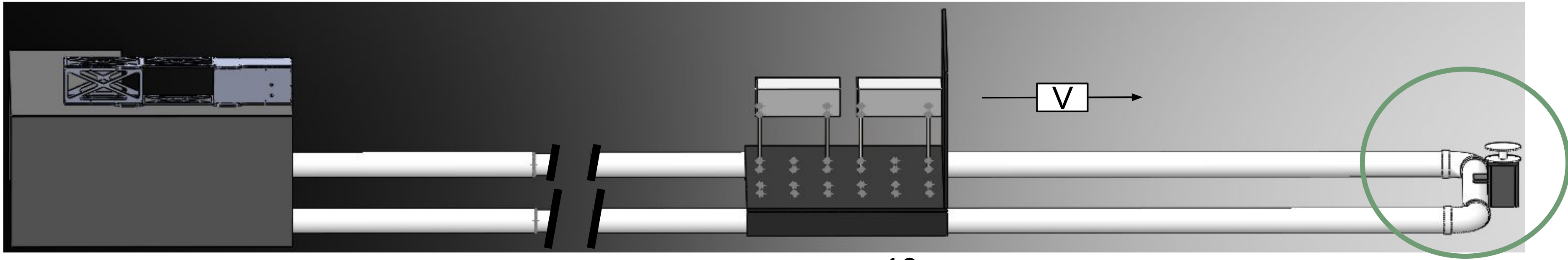
Cart holds up to 6 1U mock cubesats



Modular Test Setup

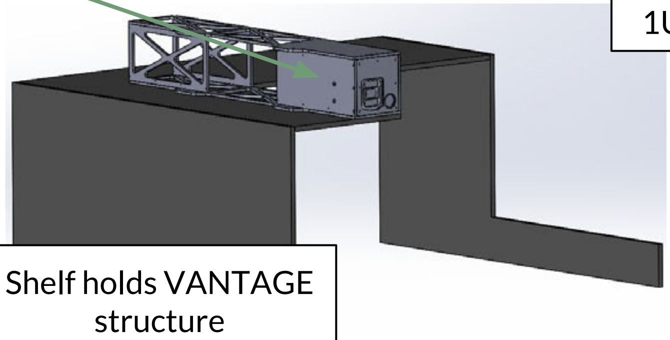
On The Ground

Full Track Not Shown



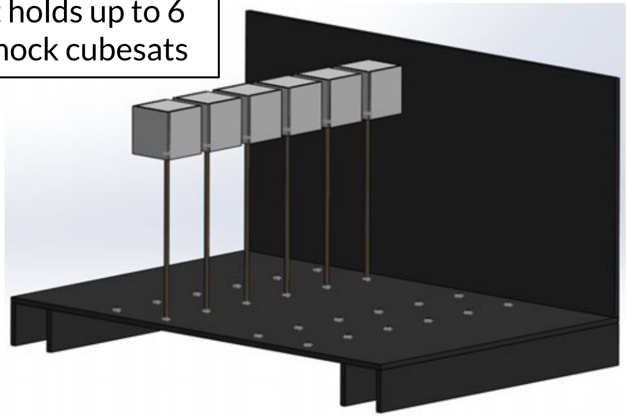
10m

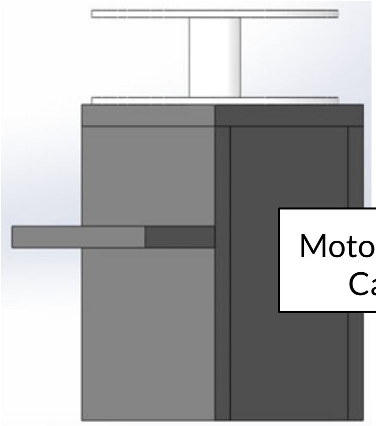
VANTAGE



Shelf holds VANTAGE structure

Cart holds up to 6 1U mock cubesats



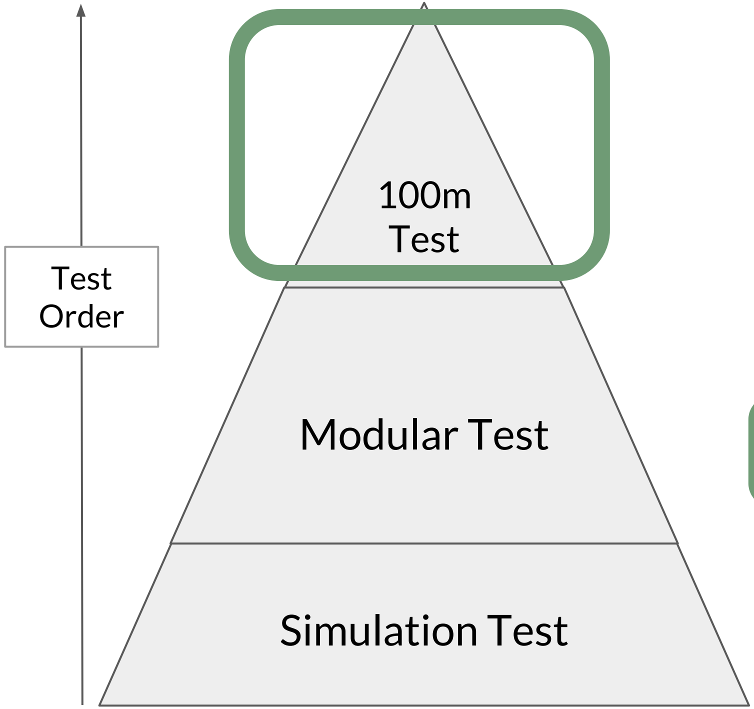


Motor pulls Cart

100 m Test System

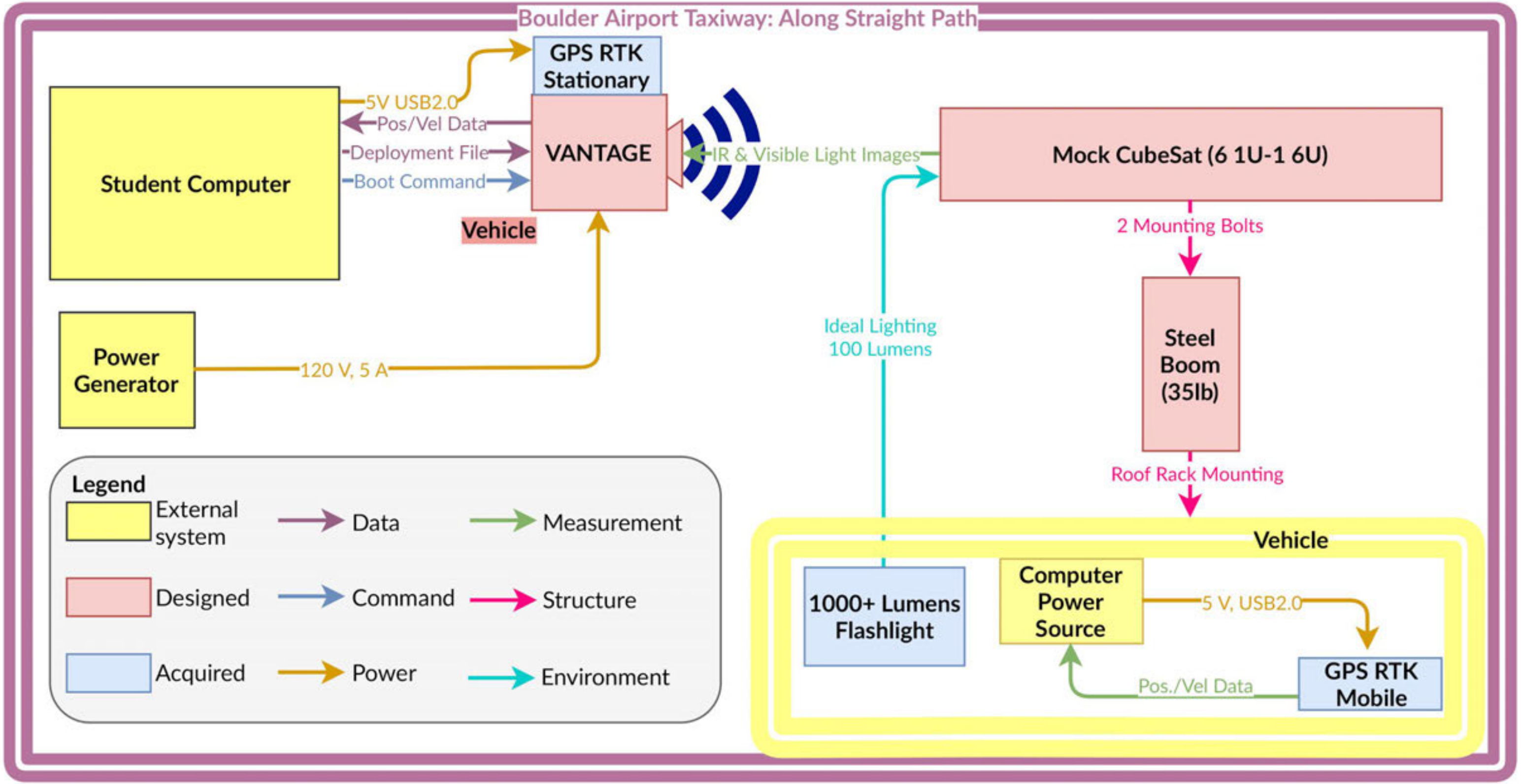
100m Test Overview

- A full scale system test of VANTAGE from power on to data return in a ground based deployment simulated environment

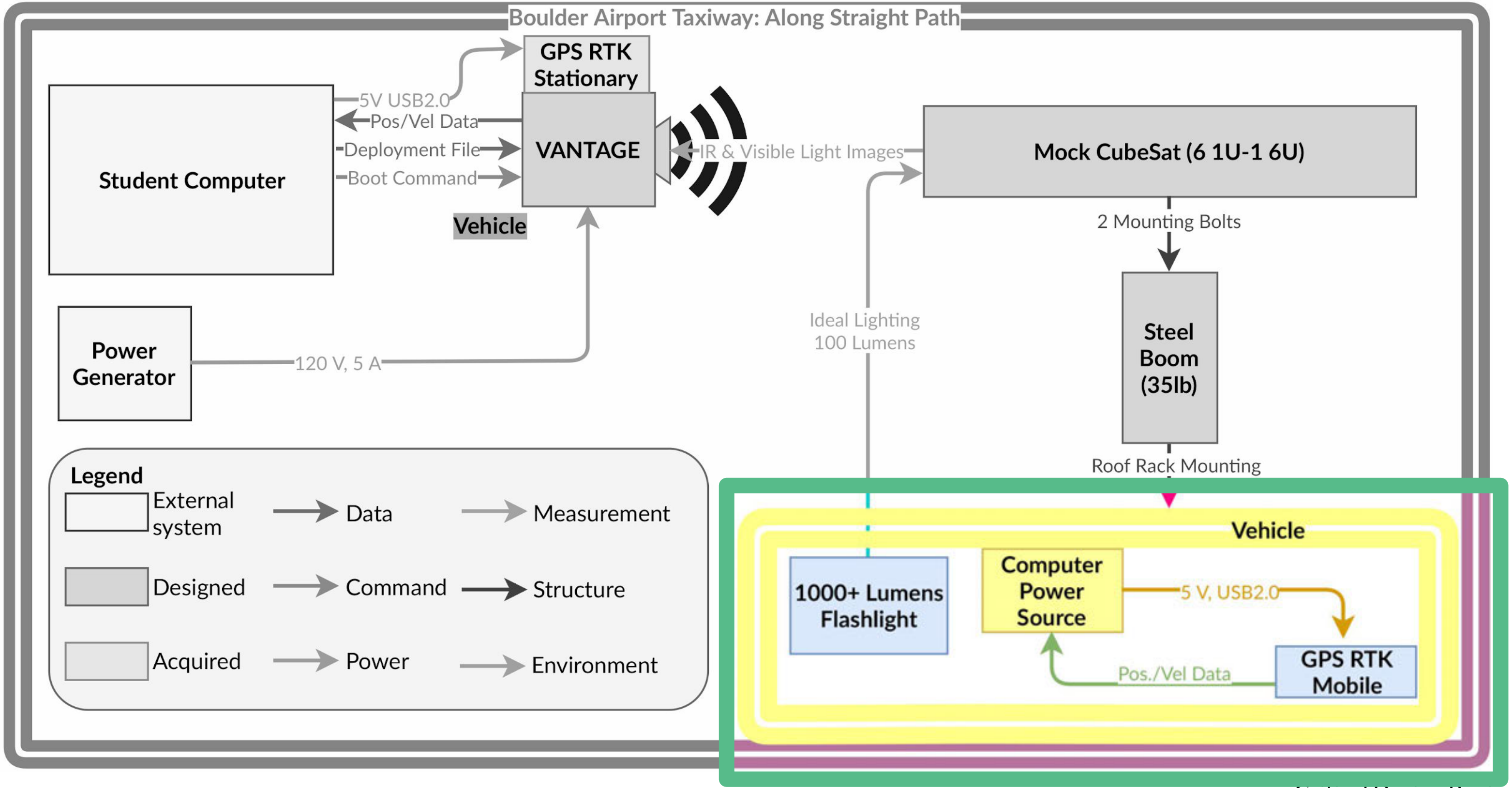


Relevant FR's: FR.1, FR.3, FR.5, FR.6	
Relevant DR's	**Summary**
DR.1.1 DR.1.3 DR.1.4	Camera system functionality and single infocus image return
DR.1.2	Imaging system field of view
DR.2.2	Interpret deployment manifest
DR.3.1 DR.3.2	System power draw and low power mode functionality
DR.5.1	Sensor subsystem
DR.5.2	Mock cubesat detection
DR.6.1 DR.6.2	Position vector and velocity vector measurements are within error bounds
DR.8.1	Report data back to the user

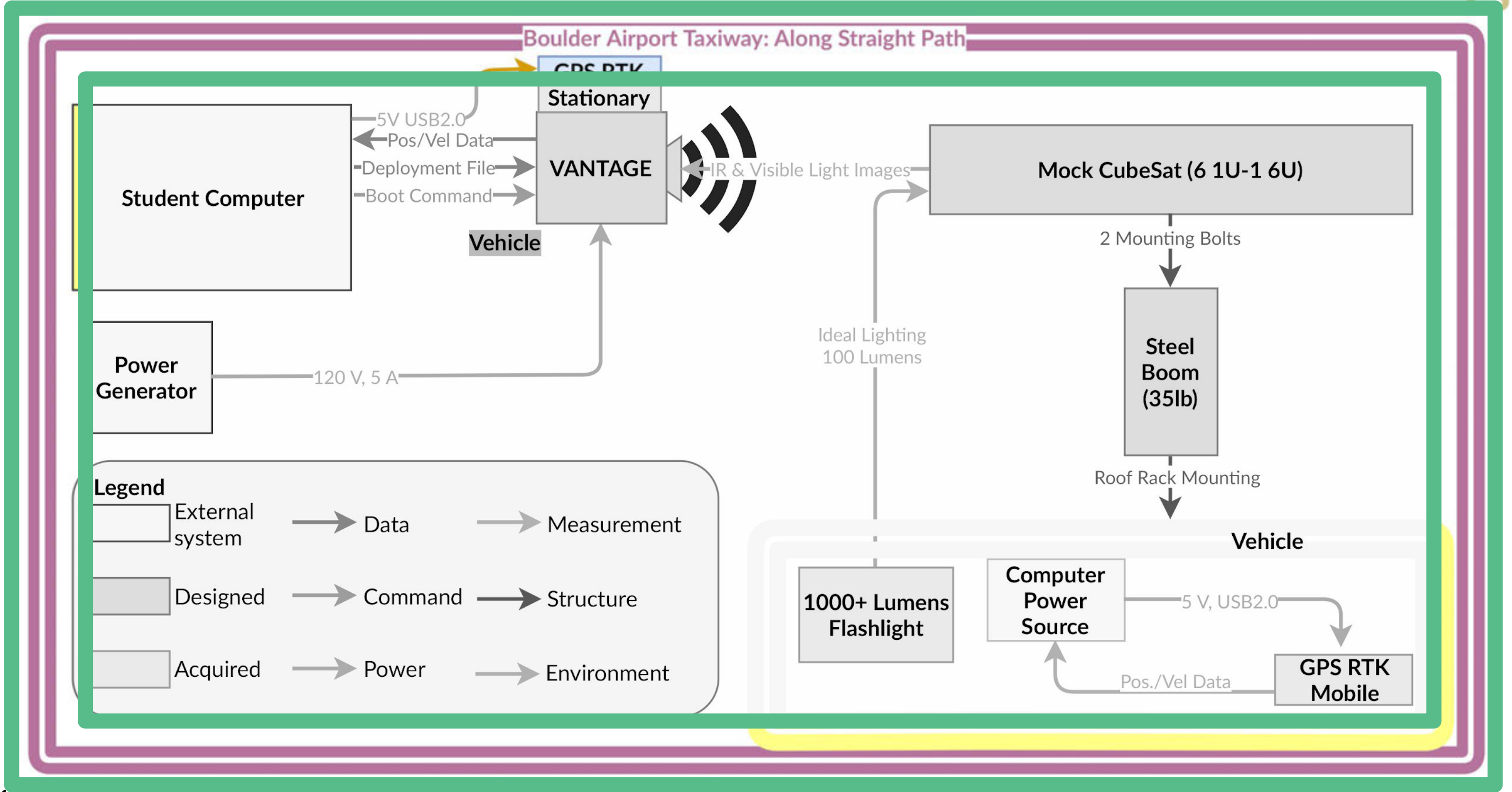
100m Test FBD



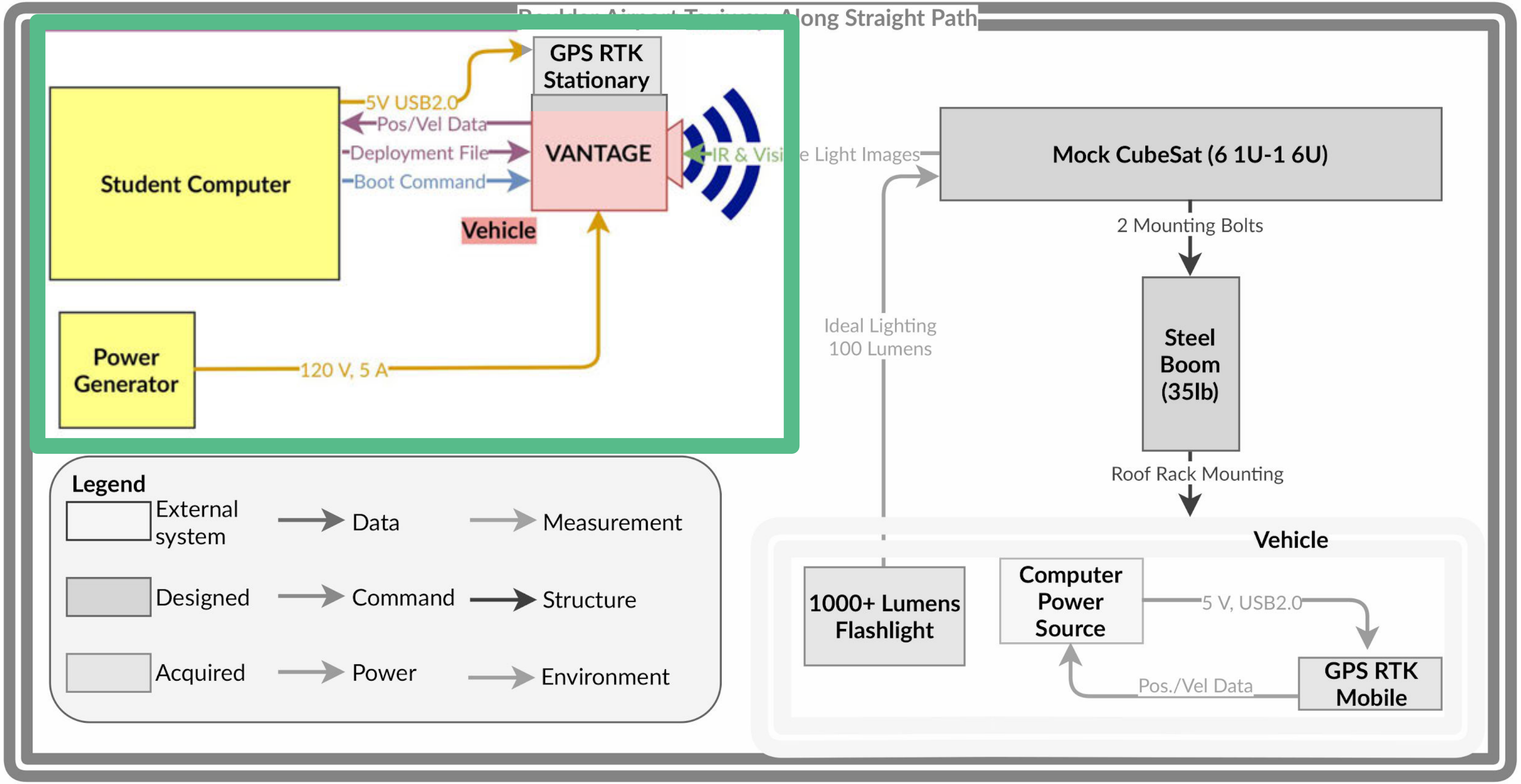
100m Test FBD



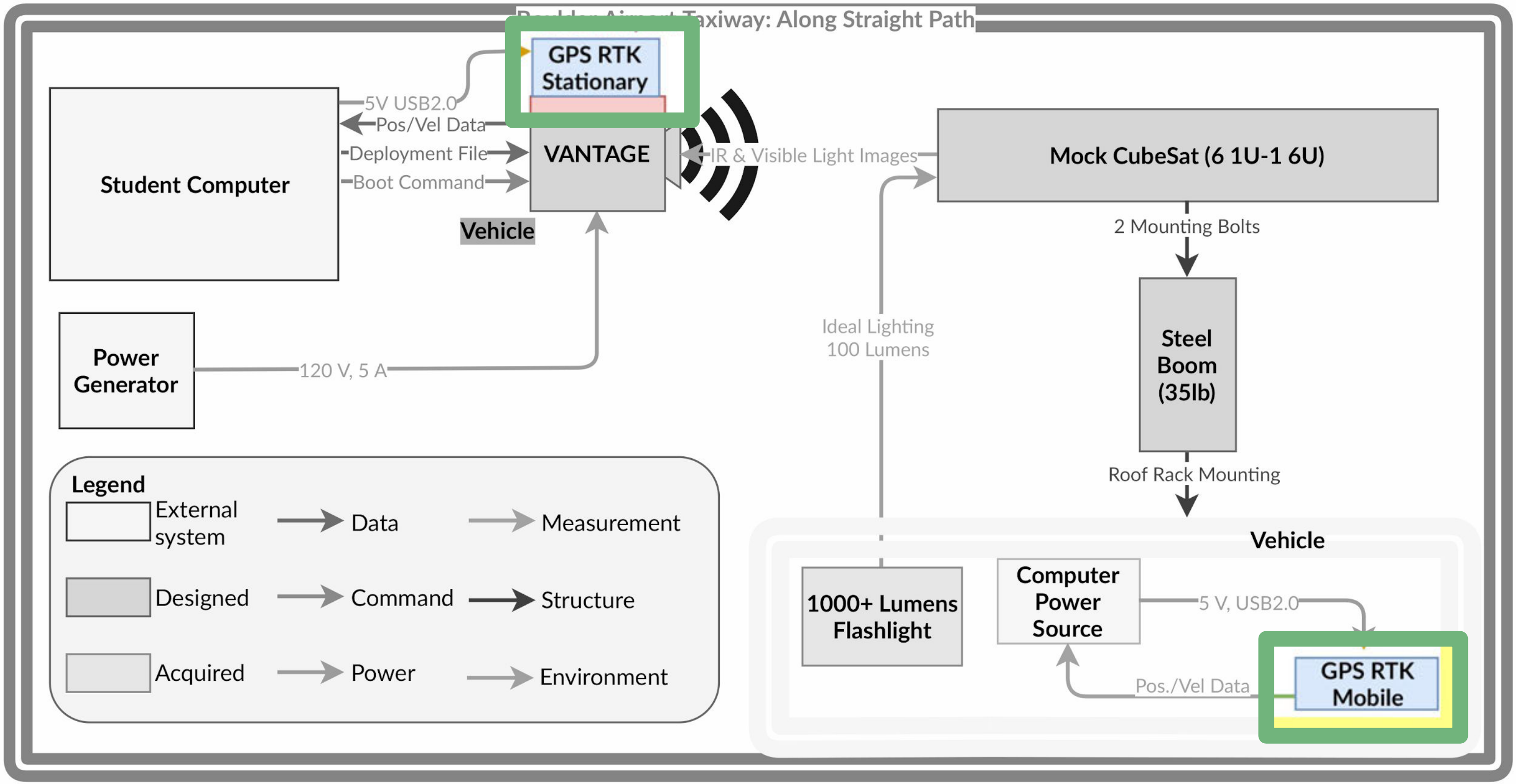
100m Test FBD



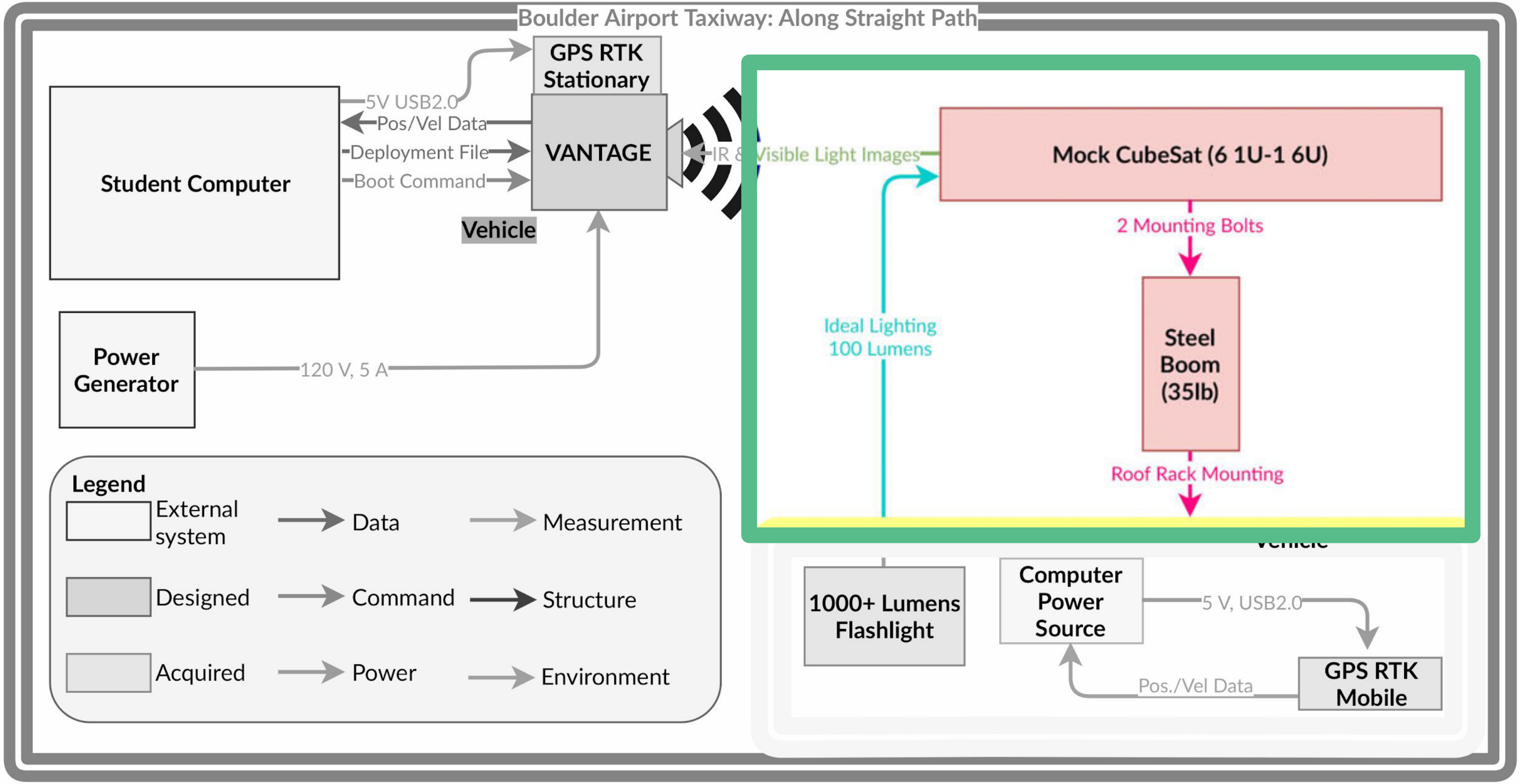
100m Test FBD



100m Test FBD



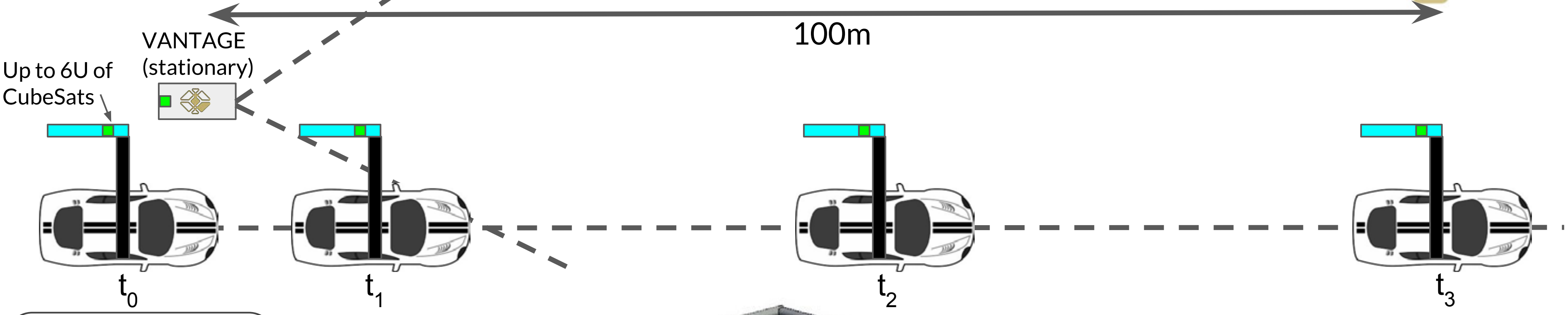
100m Test FBD



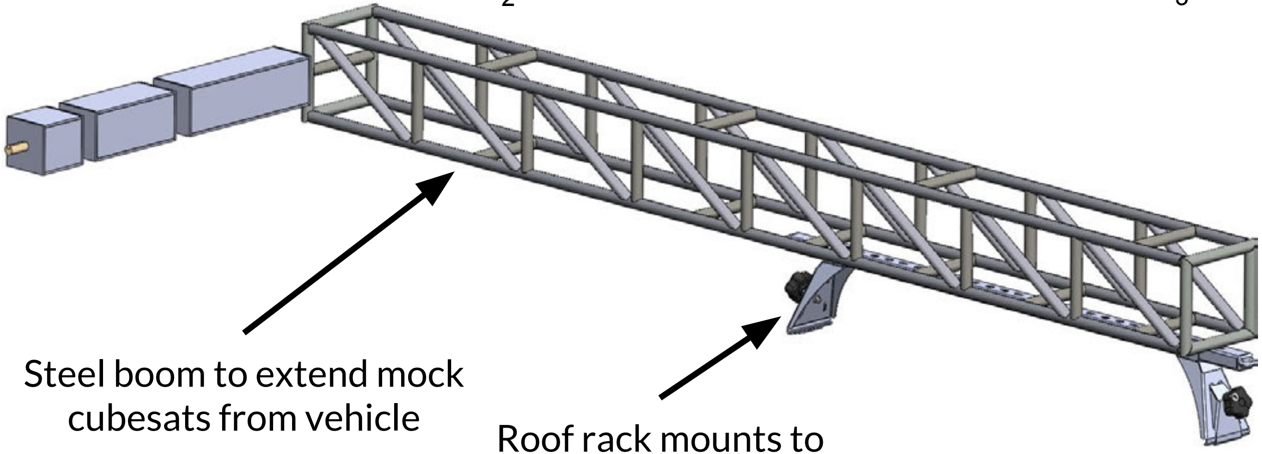
100m Test Overview

Necessary Capability/ Measurement	Hardware Used	Hardware Capability	Relevant Requirements
Truth Data **(Position & Velocity)**	GPS RTK (Real time not required, just timestamps)	Position accuracy to 2cm	**DR.6.1:** Position Accuracy (**10 cm** for 3-10 10m ,10% of range to 100 m).
		Velocity accuracy to 2cm/s	**DR.6.2:** Velocity Accuracy (**1 cm/s** to 10 m , 10cm/s to 100m)
Test Data **(Position & Velocity)**	TOF & Optical Camera (**Unit Under Test**)	N/A	**DR.6.1** & **DR.6.2**
Imaging Targets	Mock CubeSat Models	Simulates the appearance of a CubeSat	**FR.1: Images** of Mock CubeSats
Power Source	Gas powered generator	600+ W	**DR.3.1** & **DR.3.2: 120 V** power source
Various Deployment Scenarios	Cubesat Kabob	Capable of mounting all deployment scenarios	**FR.5:** Mount up to **6 1U to 2 3U** Mock CubeSats
Mock CubeSat Motion	Cubesat Test Boom and Automobile	5mph cruise control Boulder airport taxiway	**FR.6:** Mock Cubesats move with velocities between **0 and 2 [m/s].**

100m Test Setup



Legend
- CubeSat Kabob
- 10ft Test Boom
- RTK GPS units



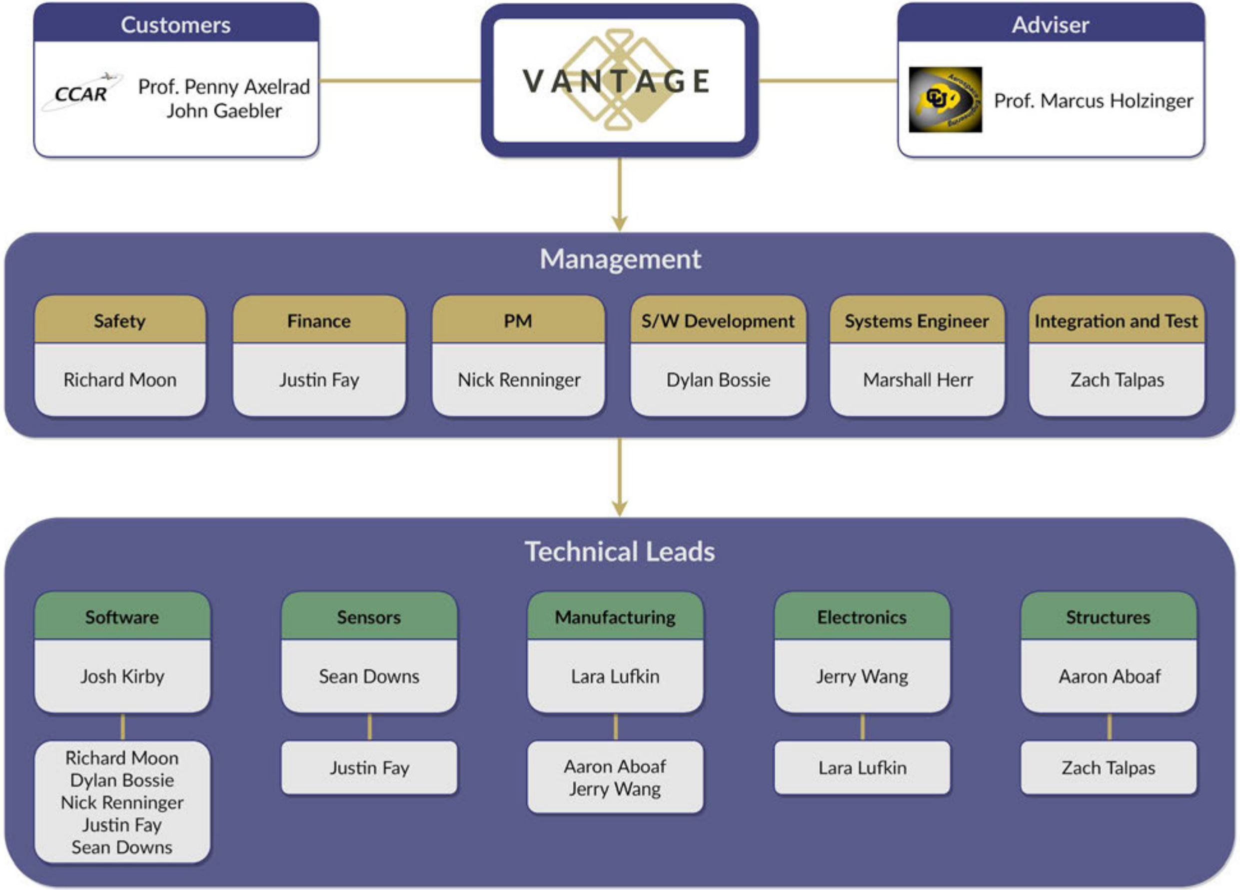
Cubesat Kabob for mock cubesat configurations

Steel boom to extend mock cubesats from vehicle

Roof rack mounts to vehicle

Project Planning

Organizational Chart



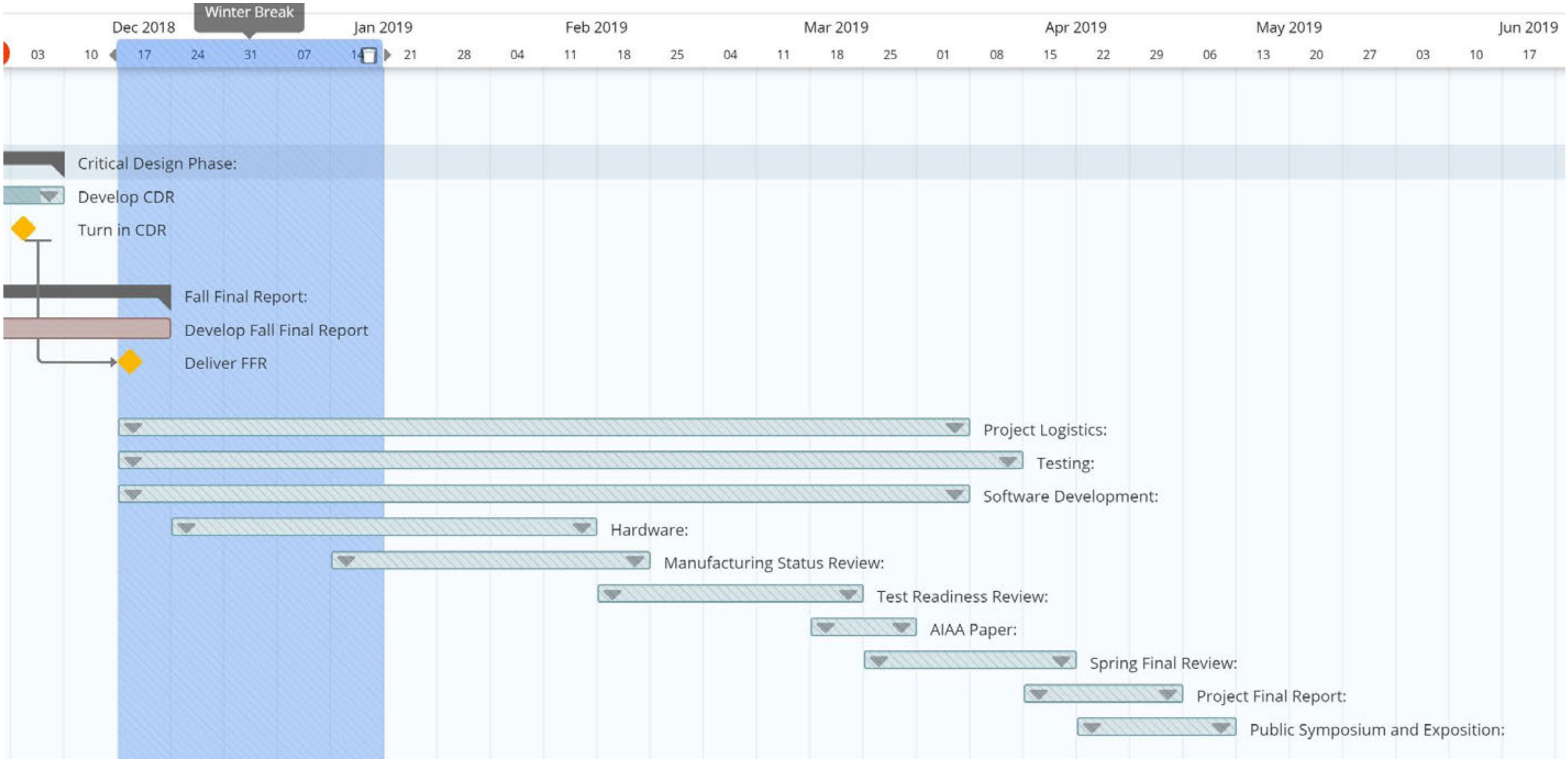
Work Breakdown Structure

VANTAGE

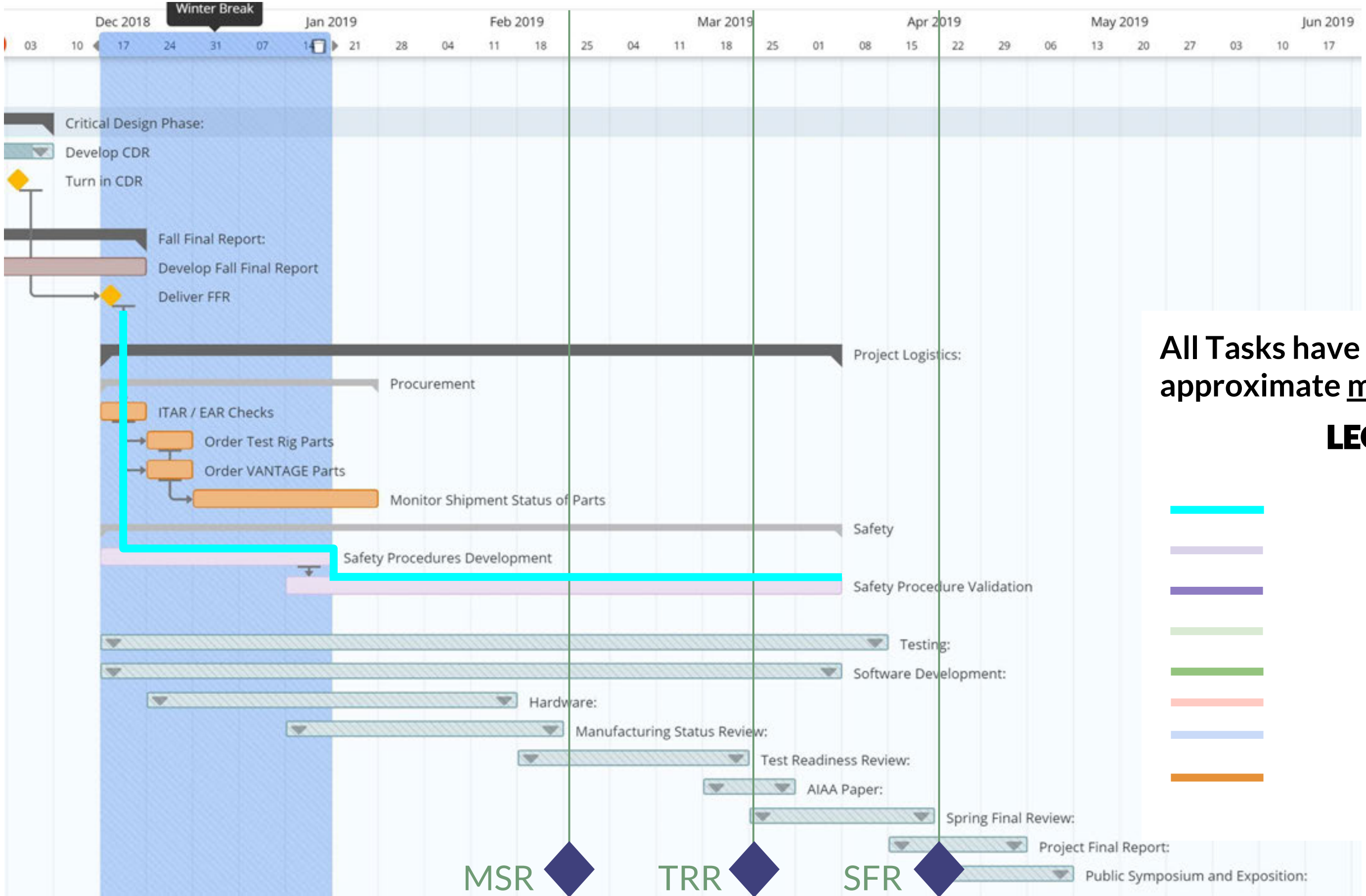
Project Breakdown

- **Project Management** — Nicholas Renninger
  - Requirements V & V — Marshall Herr
  - Financial Tracking and Procurement — Justin Fay
  - Safety Procedures — Richard Moon
- **Testing** — Zach Talpas
  - Software Integration Tests — Dylan Bossie
  - Simulation Testing — Nicholas Renninger
  - Modular Testing — Zach Talpas
  - 100m Testing — Aaron Aboaf
- **Electronics** — Jerry Wang
  - Test Electronics — Lara Lufkin
  - VANTAGE Electronics — Jerry Wang
  - Electronics Driver Testing — Lara Lufkin
- **Software Development** — Dylan Bossie
  - ToF Algorithms — Josh Kirby
  - Camera Algorithms — Richard Moon
  - Sensor Fusion Algorithms — Justin Fay
  - Sensor Simulation — Sean Downs
- **Hardware** — Aaron Aboaf
  - Manufacturing — Lara Lufkin
  - Sensor Calibration / Characterization — Sean Downs
  - Electronics Integration — Jerry Wang
  - Assembly — Aaron Aboaf

Work Plan: Overview



Work Plan: Logistics

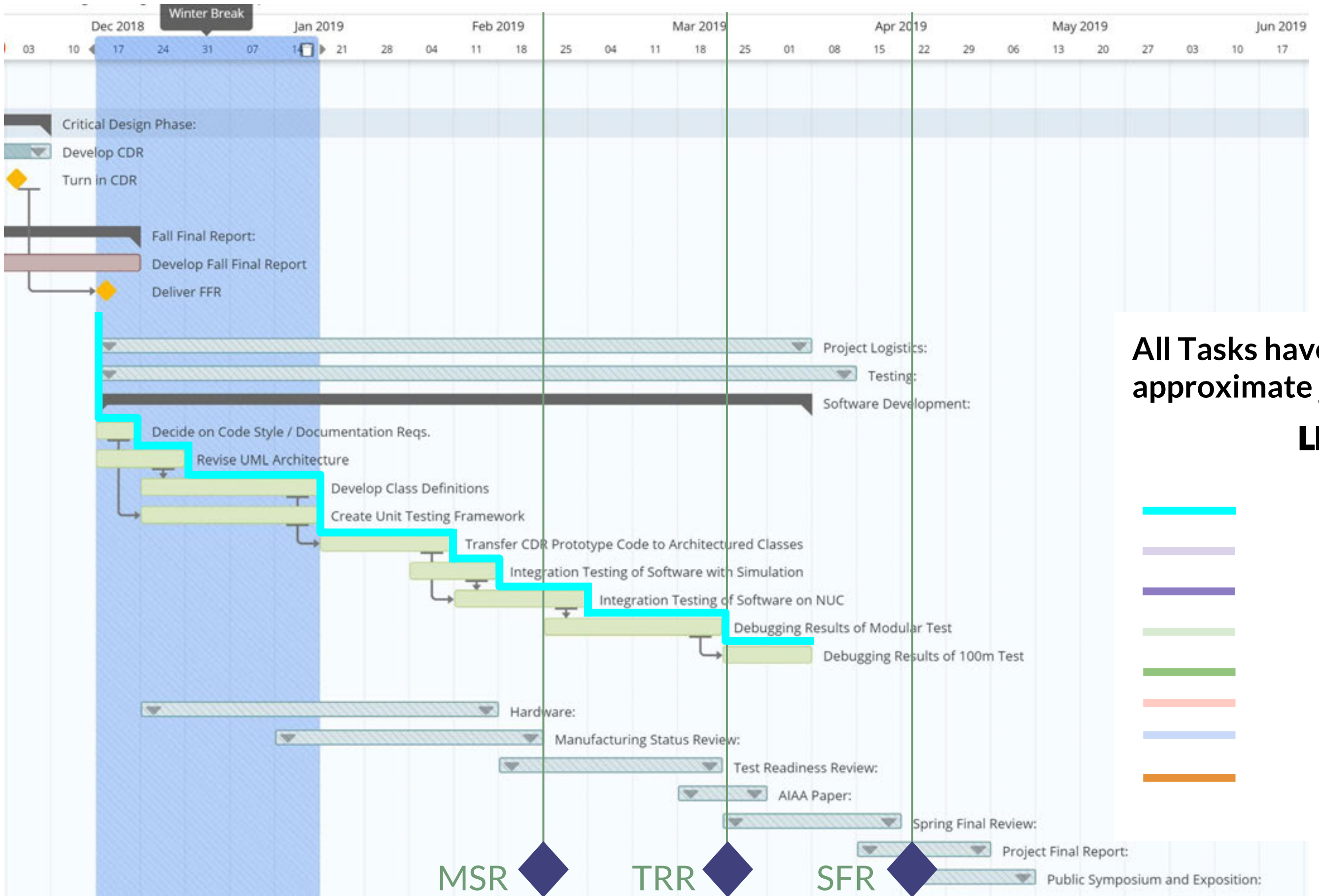


All Tasks have built in 10% approximate margin

LEGEND

Critical Path
Safety
Electronics
Software
Sensors
Structures
Testing
Finance

Work Plan: Software



All Tasks have built in 10% approximate margin

LEGEND

Critical Path
Safety
Electronics
Software
Sensors
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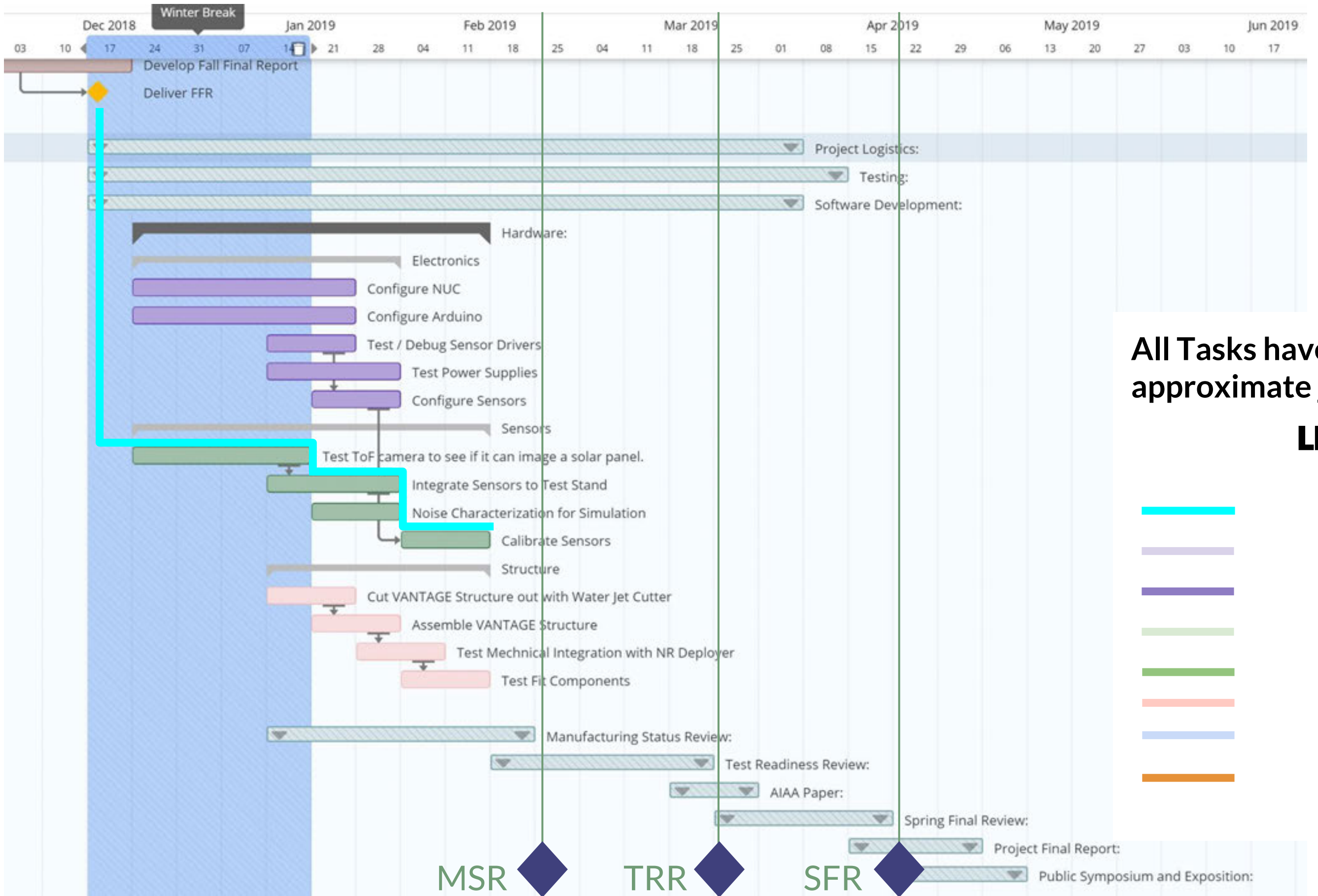
Testing
Finance

Work Plan: Hardware



All Tasks have built in 10% approximate margin

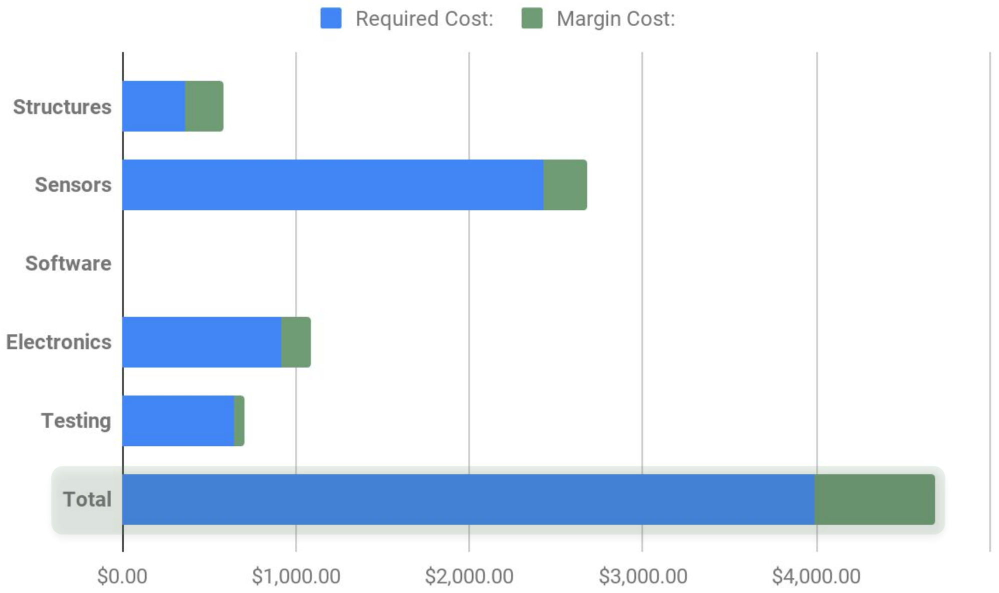
LEGEND

Critical Path
Safety
Electronics
Software
Sensors
Structures
Testing
Finance

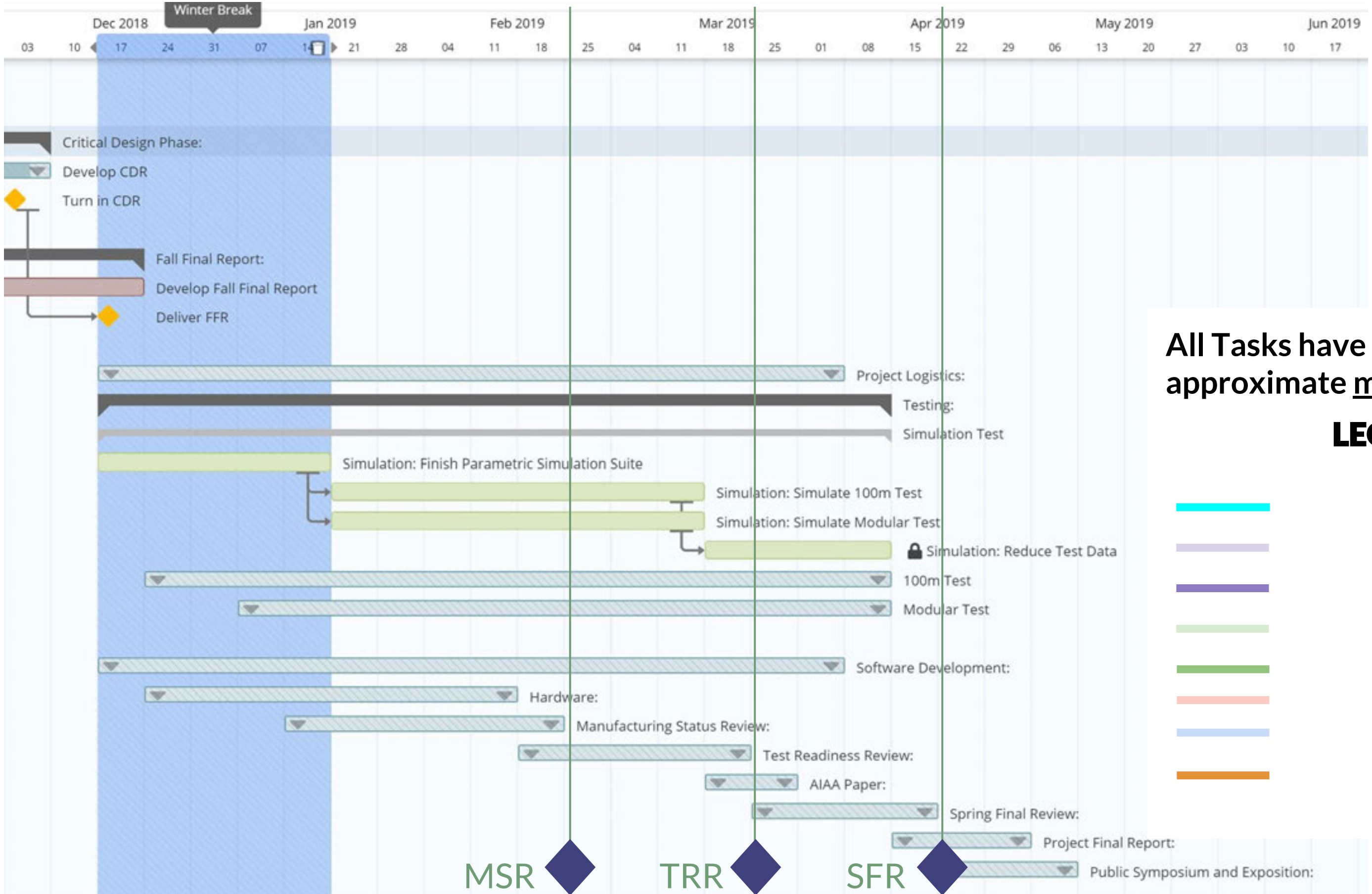
Cost Plan

	Structures	Sensors	Software	Electronics	Testing	Total
Required Cost:	$365.86	$2,430.00	$0.00	$916.22	$645.85	**$3,992.07**
Margin Cost:	$215.86	$245.00	$0.00	$175.00	$56.86	**$692.72**
Total Cost:	$581.72	$2,675.00	$0.00	$1,091.22	$702.71	**$4,684.79**

Total Margin
17.35%



Test Plan: Simulation

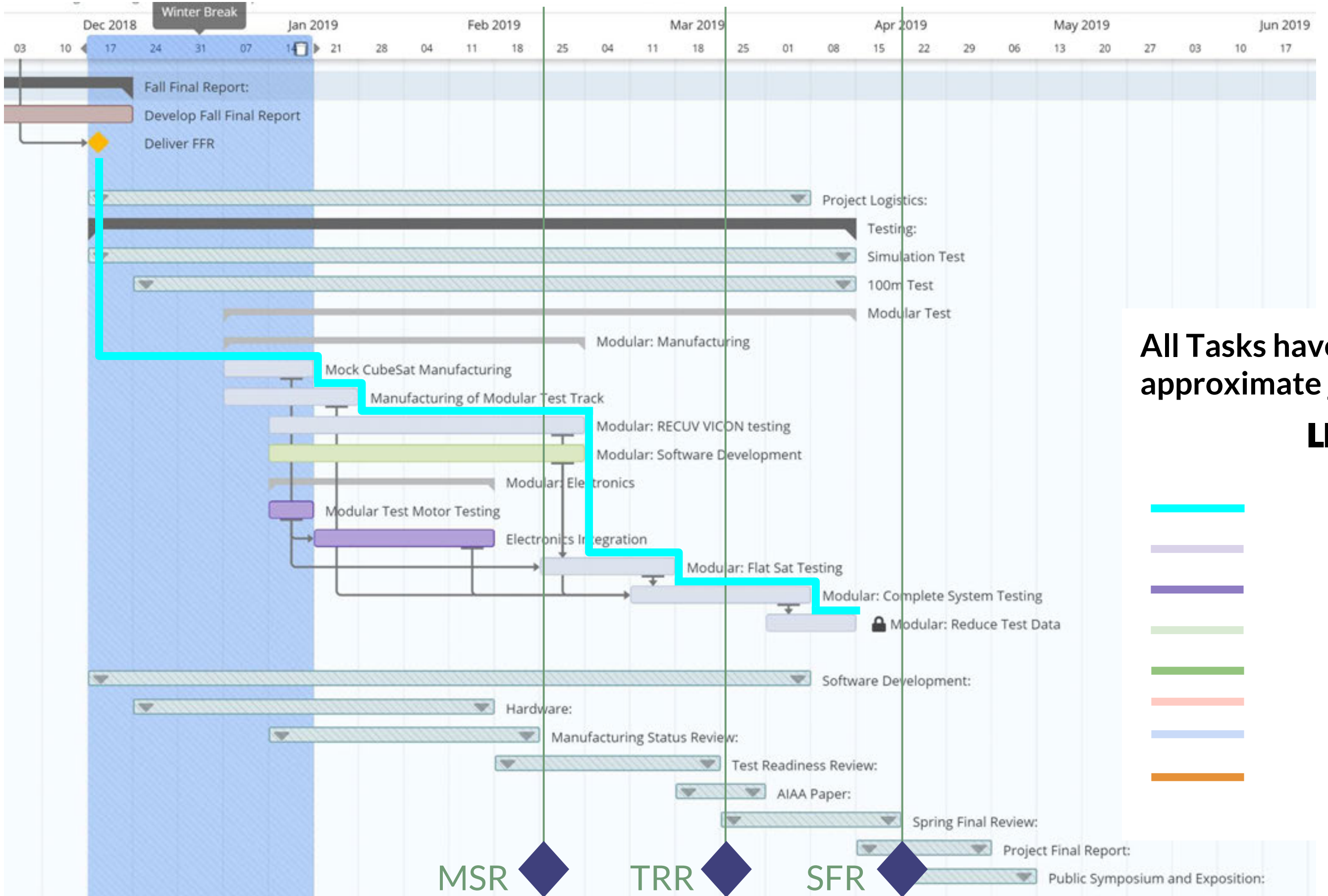


All Tasks have built in 10% approximate margin

LEGEND

Critical Path
Safety
Electronics
Software
Sensors
Structures
Testing
Finance

Test Plan: Modular Test



All Tasks have built in 10% approximate margin

LEGEND

Critical Path
Safety
Electronics
Software
Sensors
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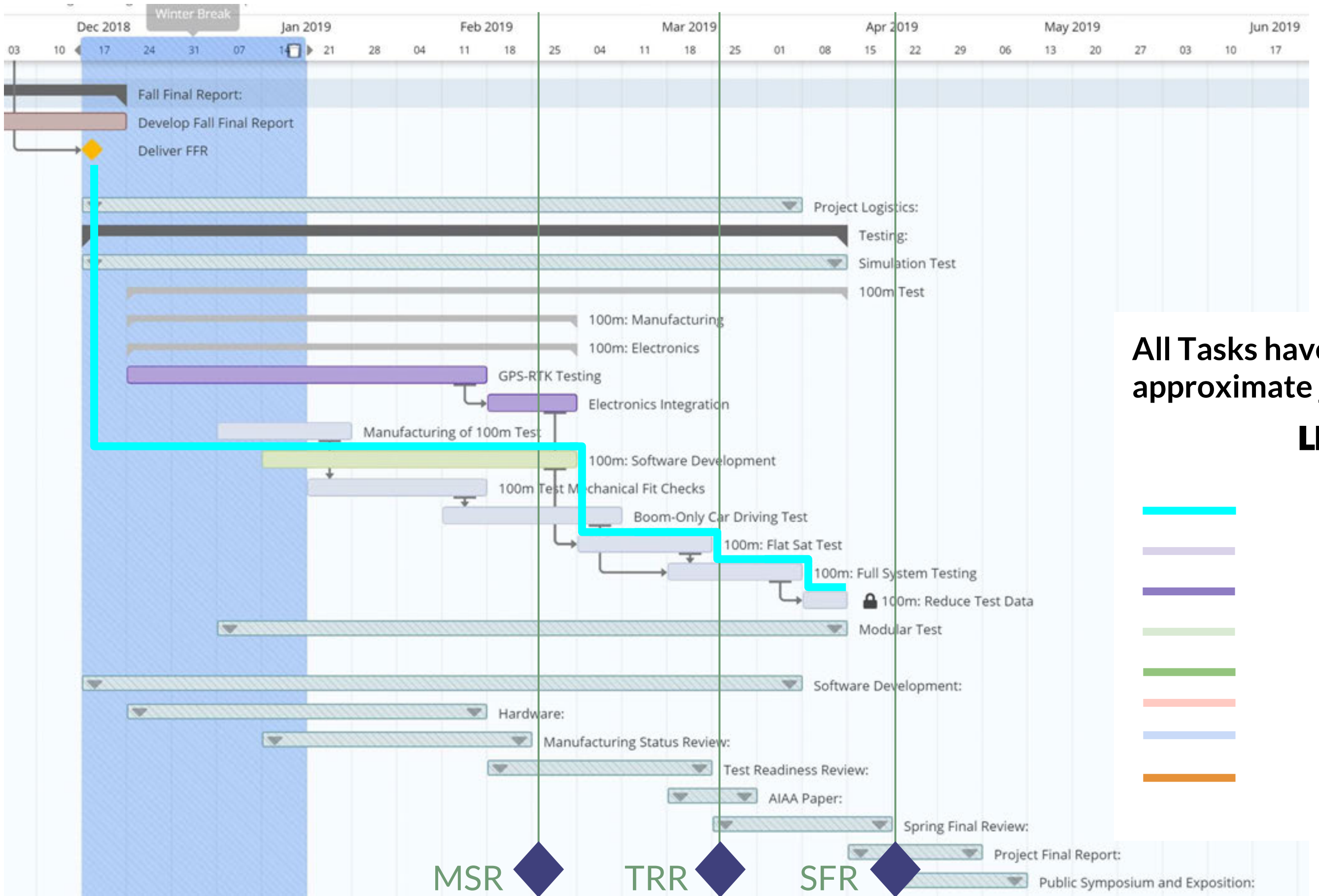
Test Plan: 100m Test



All Tasks have built in 10% approximate margin

LEGEND

	Critical Path
	Safety
	Electronics
	Software
	Sensors
	Structures
	Testing
	Finance

Testing Hardware / Facilities

Test Rig	Specialized Testing Equipment / Facilities Needed	Acquisition Status
Simulation	C4D and Blensor	Three remote team workstations with full simulation suite installed
Modular	Nema 34 Stepper Motor/Leadshine Motor Controller	Borrowed from Trudy
Modular	RECUV VICON Lab	Written approval from Steve McGuire
100 m	Boulder Airport Road	Verbal permission from FBO; Pending written approval from airport manager
100 m	Jerry's Car	Written approval from Jerry
100 m	C94-M8P ublox GPS RTK	Borrowed from Dr. Akos

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Questions?

Table of Contents

Backup Slides

Backup Table of Contents

Requirements List

Requirements List

Req.	Full Description
FR.1	The system shall support in-focus imaging of at most 6 mock 1U CubeSats at some range between 3 and 100 meters from the VANTAGE payload.
DR.1.1	The system shall use a camera to capture images of mock CubeSats.
DR.1.2	Imaging subsystem shall have a FOV greater than 20°x20°.
DR.1.3	Imaging subsystem shall produce at least 2 images of each mock CubeSat deployed by the test system.
DR.1.4	Imaging subsystem shall produce in-focus images of mock CubeSats.
FR.2	The system shall receive and interpret commands and the deployment manifest from a PC which simulates the NanoRacks use-case system.
DR.2.1	The electronics subsystem shall interface with the PC which simulates the NanoRacks use-case system via a USB2.0 Port for all data communication needs.
DR.2.2	Software subsystem shall interpret a deployment manifest file sent from the PC which simulates the NanoRacks use-case system.

Requirements List

Req.	Full Description
FR.3	The system shall accept power analogous to that which is available from the NanoRacks use-case system.
DR.3.1	The system shall operate with up to 120 VDC with a ripple voltage of 3Vpp and less than 5 A, which simulates the power available from the NanoRacks use-case system.
DR.3.2	The system shall draw less than 520 Watts.
DR.3.3	The electronics subsystem shall enter a low power mode when not performing any operations (i.e. before a final test has been started, after a final test has been completed and all post-processing and communications have completed).
FR.4	The system shall integrate mechanically with a structural interface which simulates the NanoRacks use-case system.
DR.4.1	The VANTAGE mechanical structure shall meet the interface features and dimensions called out in the NanoRacks SILO INTERFACE REFERENCES DIMENSIONS drawing number 6EHC7.
DR.4.2	The VANTAGE team shall demonstrate mechanical integration of the VANTAGE payload structure to the NanoRacks supplied ground based NRCSD hardware.

Requirements List

Req.	Full Description
FR.5	The system shall uniquely detect and track up to 6 mock 1U-3U CubeSats while they remain between 3 and 100 m of the VANTAGE payload.
DR.5.1	Sensor subsystem shall have a sensing FOV of at least 20°x20°.
DR.5.2	The system shall detect mock CubeSats within its FOV 90% of the time over a range of 3 to 100 m if said CubeSats are part of a nominal deployment and not occluded by another CubeSat.
FR.6	The system shall estimate the position and velocity vectors of CubeSats between a distance of 3 and 100 m.
DR.6.1	Software subsystem shall produce relative position vector estimates accurate up to 10 cm 1σ to a distance of 10 m, changing to an accuracy of at least a tenth of the range 1σ up to a distance of 100 m.
DR.6.2	Software subsystem shall provide relative velocity vector estimates accurate up to 1 cm/s 1σ to a distance of 10 m, changing to an accuracy of 10 cm/s 1σ up to a distance of 100 m.

Requirements List

Req.	Full Description
FR.7	The system shall recognize off-nominal deployment cases, which shall include off-nominal relative initial velocities and off-nominal deployment times from the test system.
DR.7.1	Software subsystem shall maintain current time, synchronized with global time UTC, from the PC which simulates the NanoRacks use-case system with an accuracy of at least ±1 ms.
DR.7.2	Software subsystem shall recognize if mock CubeSats exit the test system greater than 3 seconds before/after predicted with a tolerance of 0.5 seconds 3σ.
DR.7.3	Software subsystem shall recognize if initial relative velocities of mock CubeSats are less than 0.5m/s or greater than 2.0m/s with a tolerance of 0.1m/s 3σ.
FR.8	The system shall report position/velocity vector measurements, off-nominal deployment cases, and raw images from the current mock deployment to the PC which simulates the NanoRacks use-case system before the next NanoRacks CubeSat Deployer (NRCSD) tube deployment would normally occur in the use-case.
DR.8.1	The electronics subsystem shall transmit all relative position and velocity vector estimates and uncertainties, as well as mock CubeSat deployment images back to the PC which simulates the NanoRacks use-case system within 15 minutes of final mock CubeSat deployment.
DR.8.2	The system shall store all images, sensor data, and estimates within an onboard data storage device.

Risk Backup

All Risks

RISK ID	IF	THEN	ORIGINAL SEVERITY	ORIGINAL PROBABILITY	RISK SCORE	MITIGATION STRATEGIES	POST-MITIGATION SEVERITY	POST-MITIGATION PROBABILITY	POST-MITIGATION RISK SCORE
SW CMP 1	Software team encounters blocks during development.	Significant man hours invested to fix issues.	4	4	16	Well developed models Highly Architectured / diagramming Simulation of sensors to do unit testing	3	2	6
TST MOD 2	Test structure interferes with data measurement.	Modular test unable to produce usable data.	4	4	16	Use IR black paint to obscure test rig to TOF and optical sensor Use Stop motion and simulation to verify all requirements	1	3	3
AVI COM M 1	Arduino fails to remotely turn on NUC	NUC is never booted, mission entirely fails	4	3	12	Multiple methods of booting the NUC developed	3	2	6
STR	Competition for machine shop time prevents structural	VANTAGE structure is not				We are using the PHYS water jet for rapid manufacturing at low cost We will begin manufacturing of large test			

RISK ID	IF	THEN	ORIGINAL SEVERITY	ORIGINAL PROBABILITY	RISK SCORE	MITIGATION STRATEGIES	POST-MITIGATION SEVERITY	POST-MITIGATION PROBABILITY	POST-MITIGATION RISK SCORE
SW CMP 4	Inexperienced SW team mismatches styles and SW interfaces.	Significant portions of the SW will not interface properly and will not work.	5	2	10	Lots of diagraming and meeting often	5	1	5
SW CMP 6	Improper planning causes the SW to be mismatched to the real requirements.	Code unable to function according to VANTAGE needs.	5	2	10	Well developed models, use of representative simulation environment	3	1	3
SW CMP 5	Hardware unavailable for code testing.	Code cannot be tested.	5	2	10	Have backup hardware (Trudy's NUC?)	1	1	1
SENS SN 3	Sensors are missaligned	Error grows to potentially unacceptable levels	3	3	9	Use of high accuracy mounting constructed by CNC to mount sensors	3	1	3
AVI DEV 1	Drivers for Sensors do not work	We will be unable to get sensor data	4	2	8	Perform unit testing with the drivers Test sooner rather than later	3	2	6
SENS SN 1	A single sensor fails	Error is too large to meet requirements	4	2	8	Simulation as offramp.	2	2	4
SENS TST 1	Sensors damaged during testing	Funding will have to be procured to replace said sensor.	4	2	8	Simulation as offramp.	2	2	4

All Risks

RISK ID	IF	THEN	ORIGINAL SEVERITY	ORIGINAL PROBABILITY	RISK SCORE	MITIGATION STRATEGIES	POST-MITIGATION SEVERITY	POST-MITIGATION PROBABILITY	POST-MITIGATION RISK SCORE
SENS TST 2	Representative CubeSat mock ups are IR absorbative.	TOF cannot measure mock CubeSats.	4	2	8	Use black paint to obscure test rig to TOF and optical sensor	4	1	4
TST MOD 1	Step Motor control failure.	Step motor does not run or is uncontrollable, which means we cannot get truth data or reliable movement from our test rig.	4	2	8	Use RECOV system	2	2	4
SW TST 1	Simulation improperly models real sensors.	Algorithms redeveloped to match real life.	4	2	8	Fast track real data acquisition Use accurate simulations	3	1	3
TST 100M 3	Car Drives into the Hayden Lake	Jerry has to get a new car	2	4	8	Make sure Jerry gets his optical prescription renewed Drain the Lake	1	2	2
TST MOD 5	Modular test structure is warped by continued usage	The motor might have difficulty pulling the cart along the track - we get highly non-linear velocity of our cubesat models	3	2	6	Having test offramps (stop motion)	2	2	4

RISK ID	IF	THEN	ORIGINAL SEVERITY	ORIGINAL PROBABILITY	RISK SCORE	MITIGATION STRATEGIES	POST-MITIGATION SEVERITY	POST-MITIGATION PROBABILITY	POST-MITIGATION RISK SCORE
TST 100M 1	GPS RTK system fails.	We do not get truth data for our 100m test.	3	2	6	Having test offramps (stop motion) 100m test not necessary for explicit requirement satisfaction	2	2	4
AVI DEV 2	Drivers for Sensors are difficult to get working properly	We will spend a lot of time trying to get the drivers working We could slip testing schedules	2	3	6	Perform unit testing with the drivers Test sooner rather than later	1	3	3
SW CMP 2	Testing conditions create issues that need to be resolved within the software	Significant manhours invested to fix issue.	3	2	6	Begin testing sooner rather than later.	1	2	2
TST MOD 3	Truth data system fails.	We do not get truth data for our modular test.	3	2	6	Use RECOV system	1	2	2
AVI COM M 2	Arduino fails to communicate with NUC	Launch data is never transmitted, vantage fails its reporting requirements	3	2	6	Remove Aurduino, replace boot method, communcate directly with NanoRacks simulated deployer.	1	1	1
SENS SN 2	Both sensors fail	We get no data	5	1	5	Simulation as offramp.	3	1	3

All Risks

RISK ID	IF	THEN	ORIGINAL SEVERITY	ORIGINAL PROBABILITY	RISK SCORE	MITIGATION STRATEGIES	POST-MITIGATION SEVERITY	POST-MITIGATION PROBABILITY	POST-MITIGATION RISK SCORE
STR HW 2	VANTAGE structure is damaged.	VANTAGE structure is not in a deliverable state.	5	1	5	Use PHYS shops for rapid manufacturing at low cost.	2	1	2
STR HW 3	NanoRacks interface constraints change.	VANTAGE structure will not be compliant with NanoRacks ICD.	4	1	4	Use PHYS shops for rapid manufacturing at low cost.	2	1	2
TST MOD 4	Modular test structure damaged beyond usability.	We do not get any further truth data for our modular test.	4	1	4	Having test offramps (stop motion)	2	1	2
SW CMP 3	NUC is too slow.	Code refactored to lower complexity.	4	1	4	Add a second NUC (there is room)	1	1	1
AVI PWR 1	120VDC - 24VDC Power Conversion Fails	Power is lost in entire system Could Damage TOF sensor Potentially could damage the other two DCDC converters	3	1	3	Isolation circuitry Use of lower setting on power supply/multiple supplies Extensive Bench testing with variable load meter Plug in real power last	2	1	2

All Risks

RISK ID	IF	THEN	ORIGINAL SEVERITY	ORIGINAL PROBABILITY	RISK SCORE	MITIGATION STRATEGIES	POST-MITIGATION SEVERITY	POST-MITIGATION PROBABILITY	POST-MITIGATION RISK SCORE
AVI PWR 2	24VDC - 19VDC Power Conversion Fails	Power to NUC is lost Could Damage the NUC	3	1	3	Isolation circuitry Use of lower setting on power supply/multiple supplies Extensive Bench testing with variable load meter Plug in real power last	2	1	2
AVI PWR 3	24VDC - 9VDC Power Conversion Fails	Power to Arduino Mega is Lost Damage to Arduino Mega or its Ethernet Shell	3	1	3	Isolation circuitry Use of lower setting on power supply/multiple supplies Extensive Bench testing with variable load meter Plug in real power last	2	1	2
TST 100M 2	Boom mounting deflects too much.	100m test data rendered useless.	3	1	3	Having test offramps (stop motion) 100m test not necessary for explicit requirement satisfaction	2	1	2

Project Plan Backup

CCAR

Budget Backup - Structures

VANTAGE

Subsystems:	Structures	Sensors	Software	Electronics	Testing	Total	Margin Percent	
Required Cost:	$365.86	$2,430.00	$0.00	$916.22	$645.85	$3,992.07		Total Margin
Margin Cost:	$215.86	$245.00	$0.00	$175.00	$56.86	$692.72	17.35240114	17.35%
Total Cost:	$581.72	$2,675.00	$0.00	$1,091.22	$702.71	$4,684.79		

Item Description	Req Qty	Margin Qty	Total Qty	Quantity per Pkg	Req Pkg	Margin Pkg	Req Qty Purchased	Cost per Pkg	Req Cost	Margin Cost	Extra Notes	Link
Part 002: 6061 Aluminum 1/4" x 6" x 12"	1	2	3	1	1	2	1	$14.89	$14.89	$29.78		https://ww
Part 003: 6061 Aluminum 1/4" x 6" x 12"	1	0	1	1	1	0	1	$14.89	$14.89	$0.00		https://ww
Part 005: 6061 Aluminum 1/4" x 6" x 6"	1	2	3	1	1	2	1	$8.04	$8.04	$16.08		https://ww
Part 006: 6061 Aluminum 1/4" x 6" x 6"	1	0	1	1	1	0	1	$8.04	$8.04	$0.00		https://ww
Part 007: 6061 Aluminum 1/4" x 8" x 36"	1	0	1	1	1	0	1	$51.68	$51.68	$0.00		https://ww
Part 008: 6061 Aluminum 1/4" x 8" x 36"	1	0	1	1	1	0	1	$51.68	$51.68	$0.00		https://ww
Part 009: 6061 Aluminum 1/4" x 6" x 12"	1	0	1	1	1	0	1	$14.89	$14.89	$0.00		https://ww
Part 010: 6061 Aluminum 1/2" x 1.25" x 6"	1	0	1	1	1	0	1	$3.95	$3.95	$0.00		https://ww
Part 011: 6061 Aluminum 3/4" x 3/4" x 6"	1	0	1	1	1	0	1	$3.92	$3.92	$0.00		https://ww
18-8 Stainless Steel Socket Head Screw 4-40 Thread Size, 5/8" Long	50	20	70	100	1	0	100	$4.53	$4.53	$0.00		https://ww
18-8 Stainless Steel Socket Head Screw 4-40 Thread Size, 3/8" Long	50	20	70	100	1	0	100	$4.10	$4.10	$0.00		https://ww
18-8 Stainless Steel Socket Head Screw M3 x 0.5 mm Thread, 16 mm Long	50	20	70	100	1	0	100	$5.58	$5.58	$0.00		https://ww
18-8 Stainless Steel Socket Head Screw M5 x 0.8 mm Thread, 90 mm Long	50	20	70	100	1	0	100	$6.87	$6.87	$0.00		https://ww
Zinc-Plated Steel Hex Nut Medium-Strength, Class 8, M5 x 0.8 mm Thread	50	20	70	100	1	0	100	$2.80	$2.80	$0.00		https://ww
Machining time (Phys shop)	2	2	4	1	2	2	2	$85.00	$170.00	$170.00		

Budget Backup - Sensors / Electronics

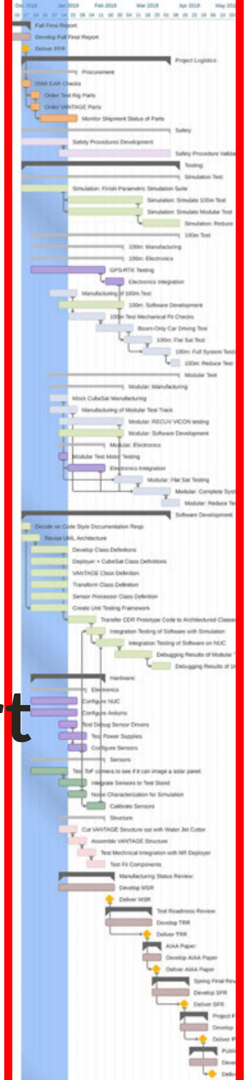
Subsystems:	Structures	Sensors	Software	Electronics	Testing	Total	Margin Percent					
Required Cost:	$365.86	$2,430.00	$0.00	$916.22	$645.85	$3,992.07		Total Margin				
Margin Cost:	$215.86	$245.00	$0.00	$175.00	$56.86	$692.72	17.35240114	17.35%				
Total Cost:	$581.72	$2,675.00	$0.00	$1,091.22	$702.71	$4,684.79						
Item Description	**Req Qty**	**Margin Qty**	**Total Qty**	**Quantity per Pkg**	**Req Pkg**	**Margin Pkg**	**Req Qty Purchased**	**Cost per Pkg**	**Req Cost**	**Margin Cost**	**Extra Notes**	**Link**
O3D313 IR ToF Camera	1	0	1	1	1	0	1	$1,460.00	$1,460.00	$0.00		https://ww
EO-6412M Monochrome USB 3.0 Camera	1	0	1	1	1	0	1	$725.00	$725.00	$0.00		https://ww
35mm MegaPixel Fixed Focal Length Lens	1	1	2	1	1	1	1	$245.00	$245.00	$245.00	May change to 16mm version	https://ww
MATLAB License	1	0	1	1	1	0	1	$0.00	$0.00	$0.00		https://oit.
Various external packages	1	0	1	1	1	0	1	$0.00	$0.00	$0.00		https://oit.
INTEL® NUC KIT NUC8I7BEH	1	0	1	1	1	0	1	$484.30	$484.30	$0.00		https://ww
500GB Solid State Drive	1	0	1	1	1	0	1	$86.99	$86.99	$0.00		https://ww
16 GB RAM	1	0	1	1	1	0	1	$99.99	$99.99	$0.00		https://ww
DC DC CONVERTER 3.3-24V 250W	2	1	3	1	2	1	2	$35.00	$70.00	$35.00		https://ww
DC/DC CONVERTER 24V 120W	1	1	2	1	1	1	1	$63.00	$63.00	$63.00		https://ww
Arduino Ethernet Shield 2	1	0	1	1	1	0	1	$44.95	$44.95	$0.00		https://ww
USB 2.0 to Ethernet / USB to RJ45	1	0	1	1	1	0	1	$9.99	$9.99	$0.00		https://ww
Cat5E straight-through patch cable	1	0	1	1	1	0	1	$18.50	$18.50	$0.00		https://ww
Arduino Mega 2560	1	2	3	1	1	2	1	$38.50	$38.50	$77.00		https://ww

Budget Backup - Testing

Subsystems:	Structures	Sensors	Software	Electronics	Testing	Total	Margin Percent	
Required Cost:	$365.86	$2,430.00	$0.00	$916.22	$645.85	$3,992.07		Total Margin
Margin Cost:	$215.86	$245.00	$0.00	$175.00	$56.86	$692.72	17.35240114	17.35%
Total Cost:	$581.72	$2,675.00	$0.00	$1,091.22	$702.71	$4,684.79		

Item Description	Req Qty	Margin Qty	Total Qty	Quantity per Pkg	Req Pkg	Margin Pkg	Req Qty Purchased	Cost per Pkg	Req Cost	Margin Cost	Extra Notes	Link
Sheathing Plywood 15/32in x 4ft x 8ft	1	0	1	1	1	0	1	$20.15	$20.15	$0.00		https://ww
Underlayment Plywood 7/32in x 4ft x 8ft	1	0	1	1	1	0	1	$15.98	$15.98	$0.00		https://ww
Black spray paint	2	2	4	1	2	2	2	$3.98	$7.96	$7.96		https://ww
1-3/8 in. White Metal Closet Pole Sockets	32	0	32	2	16	0	32	$2.48	$39.68	$0.00		https://ww
1-3/8 in. x 72 in. Hardwood Round Dowel	3	0	3	1	3	0	3	$10.49	$31.47	$0.00		https://ww
Hudson Bearings 1" Carbon Steel	4	2	6	1	4	2	4	$3.16	$12.64	$6.32		https://ww
3 in. x 10 ft. PVC Schedule 40 DWV Plain-End Pipe	8	0	8	1	8	0	8	$17.41	$139.28	$0.00		https://ww
3 in. PVC DWV 90 Degree Hub x Hub Elbow	4	0	4	1	4	0	4	$2.66	$10.64	$0.00		https://ww
Magicmend Schedule 40 3 in. Slip PVC Insider Connector	6	0	6	1	6	0	6	$5.99	$35.94	$0.00		https://ww
1/4 in. x 50 ft. White Diamond Braided Nylon Rope	1	0	1	1	1	0	1	$8.71	$8.71	$0.00		https://ww
1-1/4 in. Construction Screw	40	50	90	184	1	0	184	$7.98	$7.98	$0.00	Quantity reqd is approximate	https://ww
6000 Lumen Flashlight	1	0	1	1	1	0	1	$29.69	$29.69	$0.00		https://ww
Conduit Clamp, Steel, Zinc Plated	8	0	8	1	8	0	8	$0.83	$6.64	$0.00		https://ww
Roof Rack Bars For BMW 5 Series Touring 2010-2017	1	0	1	1	1	0	1	$139.95	$139.95	$0.00		https://ww
3/4 in. x 10 ft. Electric Metallic Tube (EMT) Conduit	12	2	14	1	12	2	12	$6.20	$74.40	$12.40		https://ww
1/8 in. Dia. x 14 in. Long Fleetweld 37-RSP E6013 Stick Welding Electrodes (5 lb. Box)	3	2	5	1	3	2	3	$12.97	$38.91	$25.94		https://ww
Steel Pan Head Phillips Screws 1/4"-20 Thread, 2" Long	20	20	40	50	1	0	50	$10.65	$10.65	$0.00		https://ww
Zinc-Plated Steel Wing Nut 1/4"-20 Thread Size, 31/64" Base Diameter	20	20	40	100	1	0	100	$10.94	$10.94	$0.00		https://ww
1 in. x 48 in. Wood Round Dowel	1	1	2	1	1	1	1	$4.24	$4.24	$4.24		https://ww

Master Gantt Chart



Structures Backup

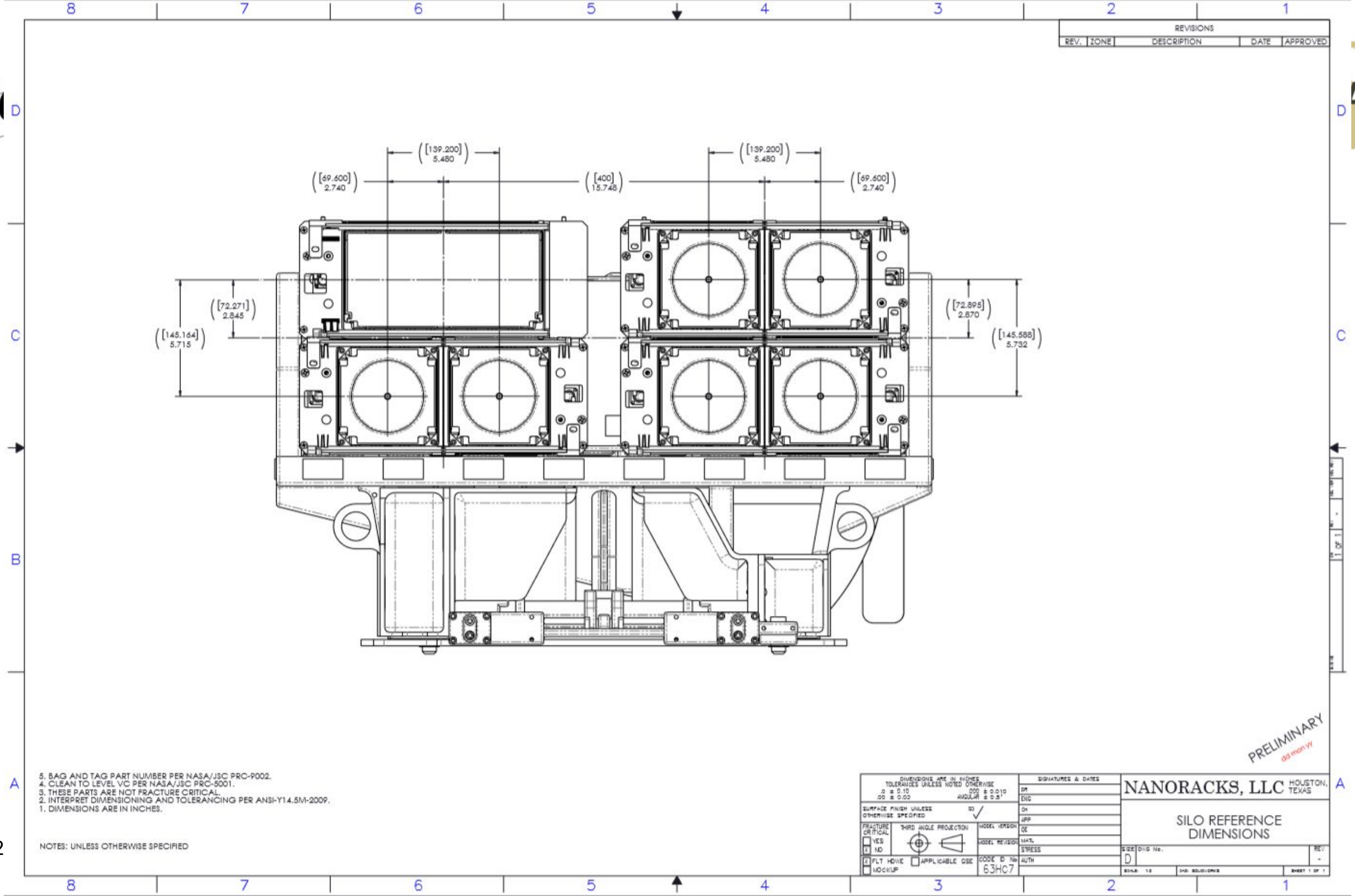
Structures Critical Project Elements

Subsystem CPEs	Governing Requirement(s)	Parent Project Objective(s)	CPE Justification
NanoRacks Hardware Compliance	DR.4.1, DR.4.2	FR.4: Mechanical Integration	The planned use case is around the NanoRacks ISS deployer system since a single VANTAGE system could be used for many launches and would always be available for use from the ISS

Req.	Description
DR.4.1-STR	The VANTAGE mechanical structure shall meet the interface features and dimensions called out in the NanoRacks SILO INTERFACE REFERENCES DIMENSIONS drawing number 6EHC7.
DR.4.2-STR	The VANTAGE team shall demonstrate mechanical integration of the VANTAGE payload structure to the NanoRacks supplied ground based NRCSD hardware.

Structures CPE Satisfaction

- Per the PDD and requirements:
  - VANTAGE mechanical design currently matches the 6EHC7 drawing called out in the requirements (Level 1)
  - Potential internal components are identified which fit within the VANTAGE mechanical structure (Level 2)
    - A low fidelity mockup of VANTAGE already demonstrates this
- Design load case:
  - Handling loads only - Rigid aluminum structure < 6kg
  - System is stationary during testing
  - Flight loads defined by SSP-57000 and SSP-57003 considered out of scope
- Internal component layout:
  - Sufficient space to house all chosen components, wire harnessing, and mounting features
  - Sensor specifications identified for future choosing of space ready hardware
- Manufacturing
  - RapidCut Quote: $1880 & 2 weeks
  - In house: ~$500 & 4 weeks
- Requirements satisfaction:
  - DR.4.1-STR - YES, the designed mechanical interface is dictated by the NanoRacks 6ECH7 drawing
  - DR.4.2-STR - YES, knowing the machining capabilities this should be satisfied trivially
  - A fit check test plan has been developed for implementation in the Spring once the mechanical structure has been built



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[145.588] 5.732
PRELIMINARY
dd mon yy
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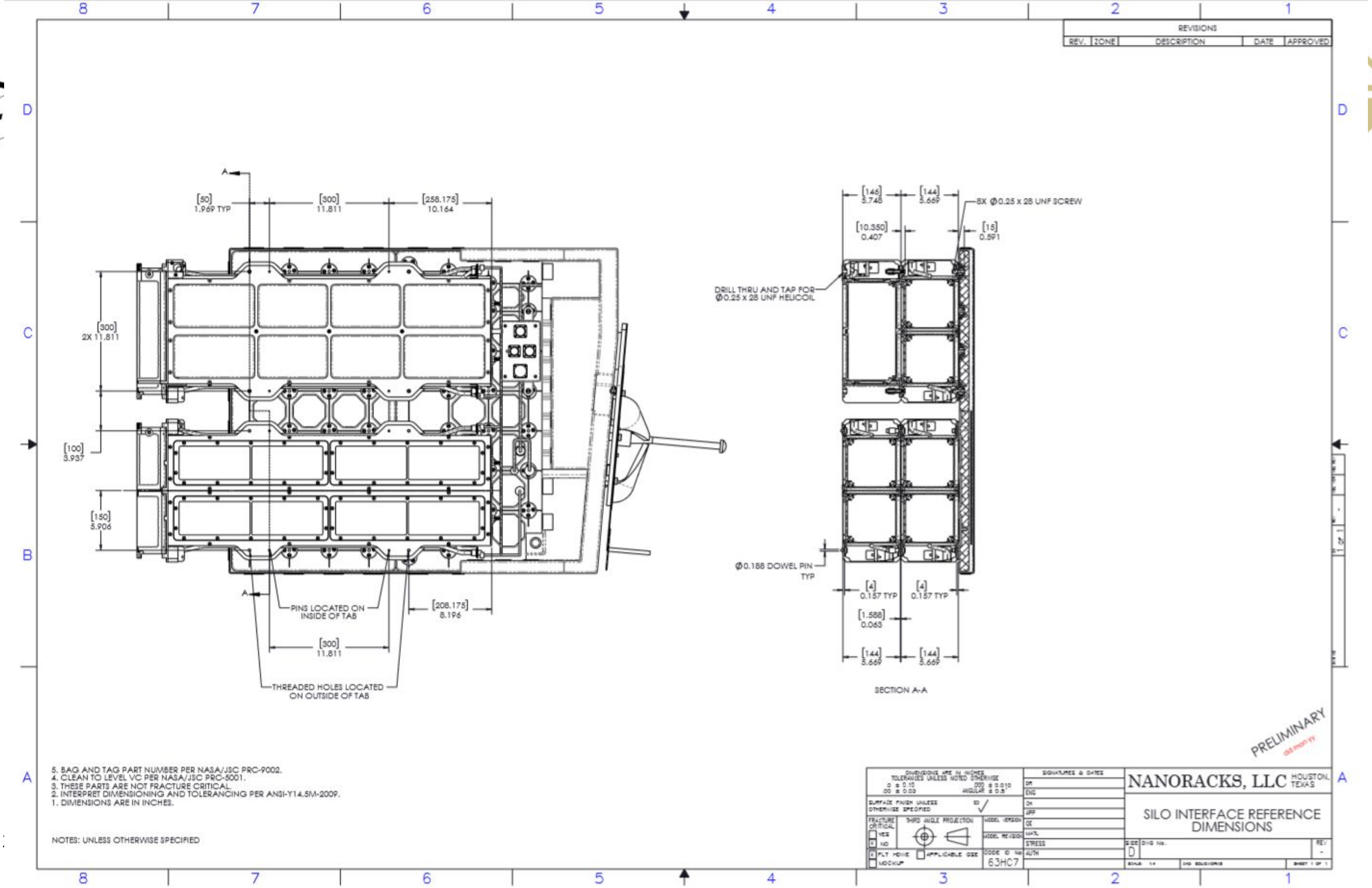
4. CLEAN TO LEVEL VC PER NASA/JSC PRC-5001.
3. THESE PARTS ARE NOT FRACTURE CRITICAL.
2. INTERPRET DIMENSIONING AND TOLERANCING PER ANSI-Y14.5M-2009.
1. DIMENSIONS ARE IN INCHES.
NOTES: UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES UNLESS NOTED OTHERWISE
SURFACE FINISH UNLESS OTHERWISE SPECIFIED
FRACTURE CRITICAL
YES
NO
THIRD ANGLE PROJECTION
FLT HDWE
MOCKUP
APPLICABLE GSE
CODE ID No
63HC7
SIGNATURES & DATES
NANORACKS, LLC HOUSTON, TEXAS
SILO REFERENCE DIMENSIONS
SIZE
D
DWG No.
REV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8X Ø0.25 x 28 UNF SCREW
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DRILL THRU AND TAP FOR Ø0.25 x 28 UNF HELICOIL
Ø0.188 DOWEL PIN TYP
[4] 0.157 TYP
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SECTION A-A
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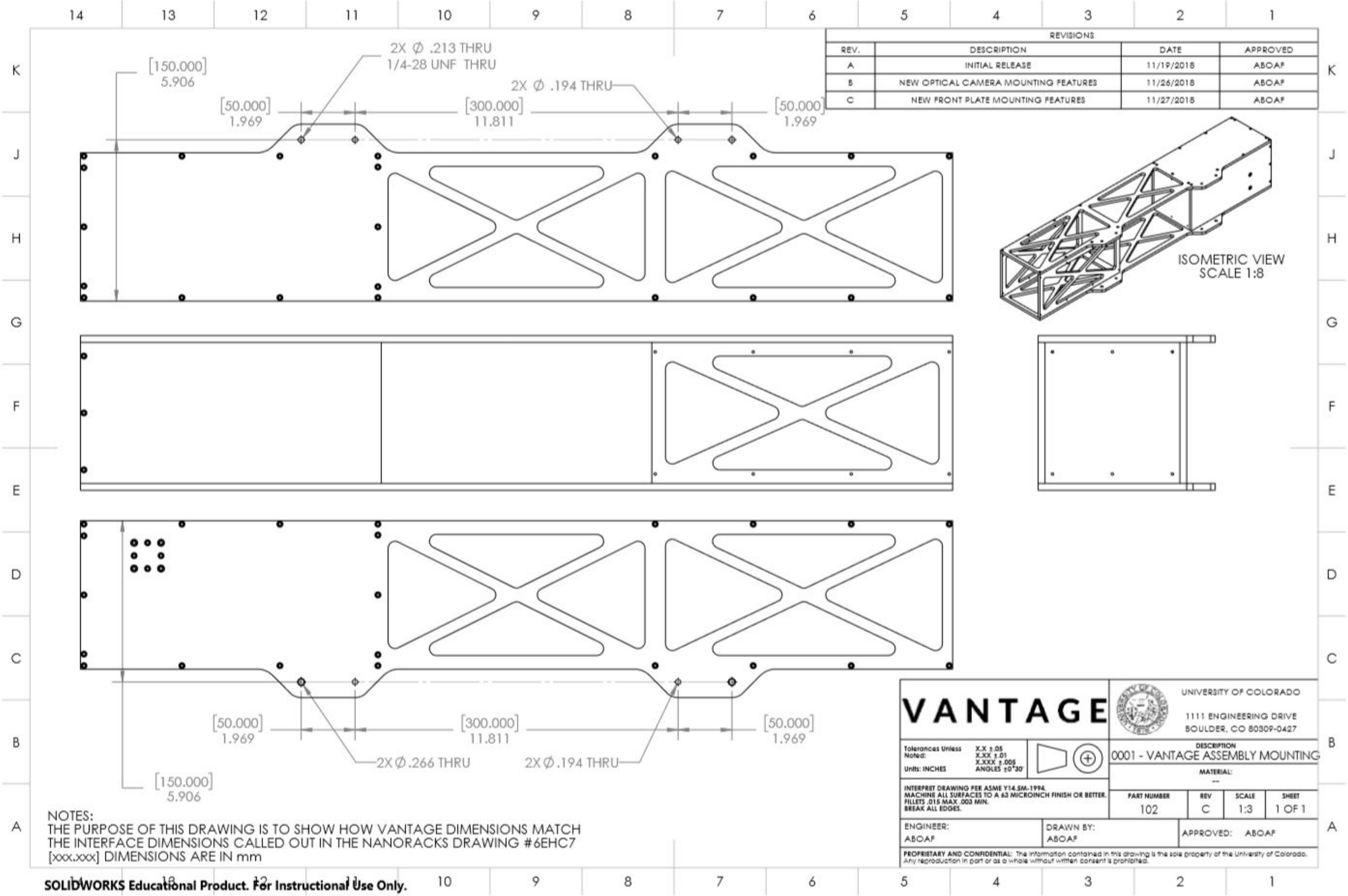
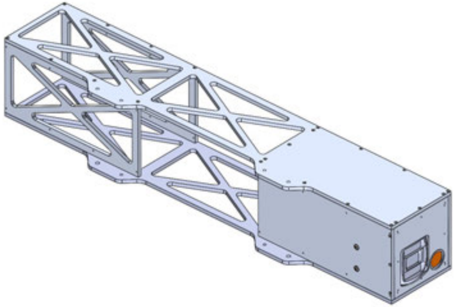
4. CLEAN TO LEVEL VC PER NASA/JSC PRC-5001.
3. THESE PARTS ARE NOT FRACTURE CRITICAL.
2. INTERPRET DIMENSIONING AND TOLERANCING PER ANSI-Y14.5M-2009.
1. DIMENSIONS ARE IN INCHES.
NOTES: UNLESS OTHERWISE SPECIFIED
NANORACKS, LLC HOUSTON, TEXAS
SILO INTERFACE REFERENCE DIMENSIONS
THIRD ANGLE PROJECTION
63HC7


REVISIONS
REV. | DESCRIPTION | DATE | APPROVED
A | INITIAL RELEASE | 11/19/2018 | ABOAF
B | NEW OPTICAL CAMERA MOUNTING FEATURES | 11/26/2018 | ABOAF
C | NEW FRONT PLATE MOUNTING FEATURES | 11/27/2018 | ABOAF
2X ∅ .213 THRU
1/4-28 UNF THRU
[150.000]
5.906
[50.000]
1.969
[300.000]
11.811
2X ∅ .194 THRU
ISOMETRIC VIEW
SCALE 1:8
2X ∅ .266 THRU
NOTES:
THE PURPOSE OF THIS DRAWING IS TO SHOW HOW VANTAGE DIMENSIONS MATCH
THE INTERFACE DIMENSIONS CALLED OUT IN THE NANORACKS DRAWING #6EHC7
[xxx.xxx] DIMENSIONS ARE IN mm
VANTAGE
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
Tolerances Unless Noted: X.X ±.05 X.XX ±.01 X.XXX ±.005 ANGLES ±0°30'
Units: INCHES
DESCRIPTION
0001 - VANTAGE ASSEMBLY MOUNTING
MATERIAL:
--
INTERPRET DRAWING PER ASME Y14.5M-1994.
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER.
FILLETS .015 MAX .003 MIN.
BREAK ALL EDGES.
PART NUMBER 102
REV C
SCALE 1:3
SHEET 1 OF 1
ENGINEER: ABOAF
DRAWN BY: ABOAF
APPROVED: ABOAF
PROPRIETARY AND CONFIDENTIAL: The information contained in this drawing is the sole property of the University of Colorado. Any reproduction in part or as a whole without written consent is prohibited.
SOLIDWORKS Educational Product. For Instructional Use Only.

Extra Structure Info

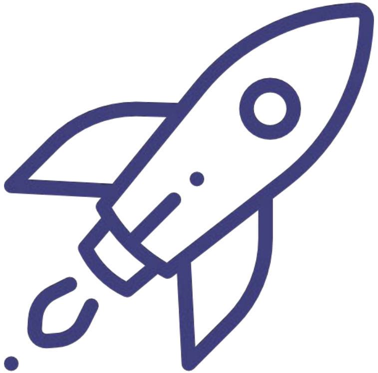
- Mass relief features included internal to component housing
  - Estimated mass ~8.2kg
- #4-40 fasteners for mounting ¼" thick Aluminum panels
  - Staked and torqued
- The back end exists because
  - NanoRacks wants us to emulate the volume of the NRCSD
  - NanoRacks doesn't have to change their packaging to go up to the ISS
  - On-orbit MLI blanket is designed to fit with the NRCSD volume
- Rear truss structure
  - Provides required mounting interface with the NanoRacks deployer silo
  - Provides structure and replicates silo interface for MLI blanket

VANTAGE’s Travel to the ISS

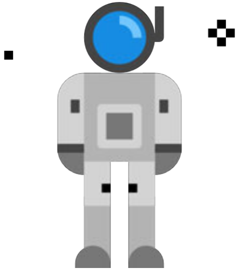


1. VANTAGE is assembled, tested, and verified on the ground

2. VANTAGE is packaged by NanoRacks as ISS bound cargo



3. VANTAGE is sent to the ISS on any qualified launch vehicle



4. Astronauts unpack VANTAGE and assemble the NanoRacks deployer

5. VANTAGE is used in the field

Structures Manufacturing Plan

- 3 Team members with Mill/CNC/SolidCAM experience - no shop training necessary
  - Additional interest from other team members to develop these skills
- Manufacturing review completed with Matt
  - Machines have been verified capable with regards to size of VANTAGE mechanical structure
  - All design based on standard imperial system tool with exception of necessary sensor mounting features
- Scheduling
  - Lighter class schedules expected in Spring semester,(during shop hours)
  - Anticipate sufficient schedule overlap between shop qualified members
  - IMS plans for 14 days of manufacturing with 14 days of margin
    - This is 100% greater than the estimated time
- No tolerances tighter than 0.005”
- Material easily sourced form McMaster
  - Budget funds available for additional material if mistake occurs
- Detailed breakdown by part on next slide

*Indicates that parts are similar in size AND complexity
**Indicates that manual mill could be used if CNC is not available

Manufacturing Part Breakdown

Part	CNC/SolidCAM?	Tools	Est. Mill Hours	Est. Prep Hours	QTY
002, 003*	Yes	EM: 1”, ¼” Drill#: 43, 7/32 Tap: 4-40	4 , 4	4	1 , 1
005	Yes	EM: ⅛”, ¼”, ½” Drill#: 30	5	4	1
006	Yes**	EM: ½” Drill#: 43 Tap: 4-40	3	4	1
007	Yes	EM: ⅛”, ½”, 1” Drill#: 43, 10, 3 Tap: 4-40, ¼-28	10	6	1
008	Yes	EM: ⅛”, ½”, 1” Drill#: 43, 30, 29, 10, 3 Tap: 4-40, ¼-28	10	7	1
009	Yes	EM: ½” Drill#: 43 Tap: 4-40	6	4	2
010	No	EM: Facing Drill#: 43, 29 Tap: 4-40	5	2	1
011	No	EM: Facing Drill#: 7/32	5	2	1
TOTAL Hours			53	33	

CCAR

Manufacturing Stock Breakdown

VANTAGE

Part	Part Dimensions	Stock Type	Stock Dimensions (in)	QTY	Cost
002	¼ x 5.17 x 11	Plate	¼ x 6 x 12	1	14.89
003	¼ x 5.17 x 11	Plate	¼ x 6 x 12	1	14.89
005	¼ x 5.43 x 5.67	Plate	¼ x 6 x 6	1	8.04
006	¼ x 4.93 x 5.17	Plate	¼ x 6 x 6	1	8.04
007	¼ x 6.48 x 31.89	Plate	¼ x 8 x 36	1	51.68
008	¼ x 6.48 x 31.89	Plate	¼ x 8 x 36	1	51.68
009	¼ x 5.17 x 11	Plate	¼ x 6 x 12	2	29.78
010	0.423 x 1.25 x 1.25	Bar	½ x 1.25 x 6	1	3.95
011	0.61 x 0.65 x 2.22	Bar	¾ x ¾ x 6	1	3.92
Fasteners	Various	18-8 Stainless SHCS	#4-40 SHCS ⅝” #4-40 SHCS ⅜” #M3 SHCS 16mm #M5 SHCS 90mm #M5 Nuts	1 pkg. each	36.92
TOTAL					$223.79

Manufacturing RapidCut Quote

- RapidCut Quote:
  - $1,880 with 13 days lead time
  - Saves us 3 weeks of full time work in the shop over three team members
    - This is valuable in itself since we have a lot of testing to coordinate and make sure runs smoothly
    - There will undoubtedly be issues with getting test rigs operational so having extra bodies with experience to help troubleshoot issues is invaluable.

Sets	Shipping Charges	Parts+Shipping (Working Days)	Total Value
1	$ 120.00	12+1	$ 1,880.00

Mass Budget

- Dark Grey = part is no longer in assembly
- Orange = non-mechanical component
- Masses for the NUC, power electronics, fasteners, and staking/coating, are estimates based on the MAXWELL project
- Link to Document

Part #	Description	Quantity	Part Mass (g)	Assembly Mass (g)	15% Margin Mass	Actual Mass
001	Base Plate	0	266.94	0	0	
002	Left Plate	1	361.29	361.29	415.4835	
003	Right Plate	1	367.99	367.99	423.1885	
004	Top Plate	0	266.94	0	0	
005	Front Plate	1	114.1	114.1	131.215	
006	Back Plate	1	163.89	163.89	188.4735	
007	Base Plate 6U	1	857.93	857.93	986.6195	
008	Top Plate 6U	1	919.15	919.15	1057.0225	
009	Outer Bulkhead	2	266.97	533.94	614.031	
010	Camera Mountin	1	27.72	27.72	31.878	
011	TOF Mounting B	1	34.29	34.29	39.4335	
012				0	0	
013				0	0	
014				0	0	
015				0	0	
O3D311	TOF Camera	1	1162	1162	1336.3	
EO-6412M	Optical Camera	1	52	52	59.8	
64-868	Optical Camera	1	87	87	100.05	
#	NUC	1	1440	1440	1656	
#Custom	Power Electronic	1	1000	1000	1150	
Fasteners		1	200		230	
Staking/Coating		1	200		230	
TOTALS (g)				7121.3	8649.495	0

Fit Check Test Plan (1)

- VANTAGE has received a deployer SILO (NRCSD) which will essentially act like the test rig for this fit check test
- 1. The VANTAGE mechanical structure will be assembled according to the assembly procedures document and the assembly drawing #0011
    - The necessary parts for this test are the outer plates of the mechanical housing being PN#: 002, 003, 005, 006, 007, 008, 009
- 2. The NanoRacks hardware will be unpacked and placed on a flat table and oriented to match the on orbit orientation of SILO 8
- 3. The VANTAGE mechanical structure will be oriented to match its planned orientation in place of SILO 1
- 4. The VANTAGE mechanical structure will be lifted by two people and placed on top of the NanoRacks hardware such that both guiding dowel pins interface with their respective holes on the VANTAGE mechanical structure.
    - If the dowel pins on the NanoRacks hardware SILO do not fit into the dowel pin holes on the VANTAGE structure this test shall be considered a failure

Fit Check Test Plan (2)

- 5. Once the dowel pin interface has been checked, two ¼”-28 x ½” socket head cap screws will be hand threaded through the clearance holes on the VANTAGE mechanical structure into the threaded holes of the NanoRacks hardware SILO
    - These will be hand threaded at first to prevent damage to the threaded holes of the NanoRacks hardware
    - If there is considerable resistance to start hand threaded or these clearance holes on the VANTAGE mechanical structure do not align with the threaded holes on the NanoRacks hardware well enough to support easy hand threading this test shall be considered a failure
- 6. Once hand threading is complete, the ¼”-28 socket head cap screws will be torqued using a torque wrench. Torque to 57in · lbs
    - If the fasteners are unable to to torqued properly either due to head or thread stripping then this test shall be considered a failure
- 7. The VANTAGE mechanical structure will then be gripped by hand to ensure that it is secured well to the NanoRacks hardware SILO
    - If the VANTAGE mechanical structure moves significantly (feels loose of insecure because it moves more than 0.01” when a handheld force is applied) then this test shall be considered a failure
- 8. The ¼”-28 fasteners should then be removed
    - If the fasteners are unable to be removed with only the use of a torque screwdriver and allen key then this test shall be considered a failure

Extra Info & NASA Docs

- All Coatings(lens coatings, housings, etc.) should have low outgassing properties.
- Electronics(CMOS image sensors, internal processors) may need to be radiation hardened.
- Components should have appropriate operational and storage temperature ranges.
- Governing NASA documents
  - NASA SSP 57003 External Payload Interface Requirements Document for the International Space Station Program (rev L)
  - NASA SSP 30237 Space Station Electromagnetic Emission and Susceptibility Requirements for the International Space Station (rev T).

- Exactly replicates the required NRCSD mounting features
  - Interface mounting to NR NRCSD using two ¼”-28 bolts
  - Has two ¼”-28 threaded holes for MLI blanket mounting
- Sensors mounted internally using fitted bulkheads
  - Sensor mounting allows for fine tuned adjustment

Mechanical Drawings (1)

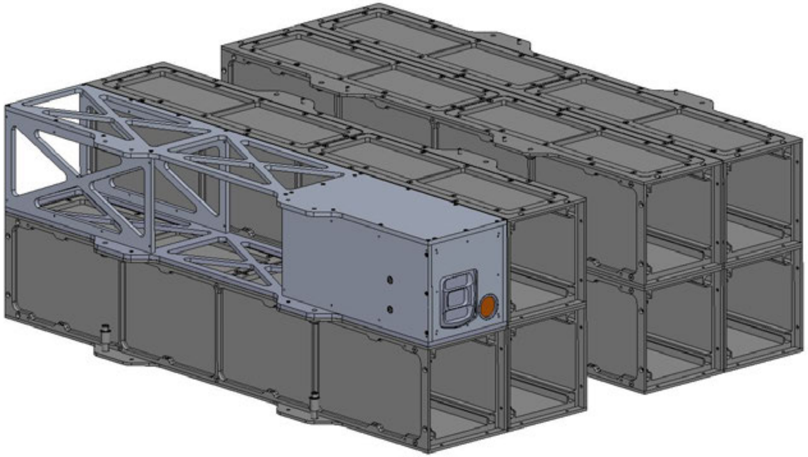
- Please see the table below for descriptions of each drawing
- The PDFs can be found in this FOLDER and are also printed for the convenience of the reviewers

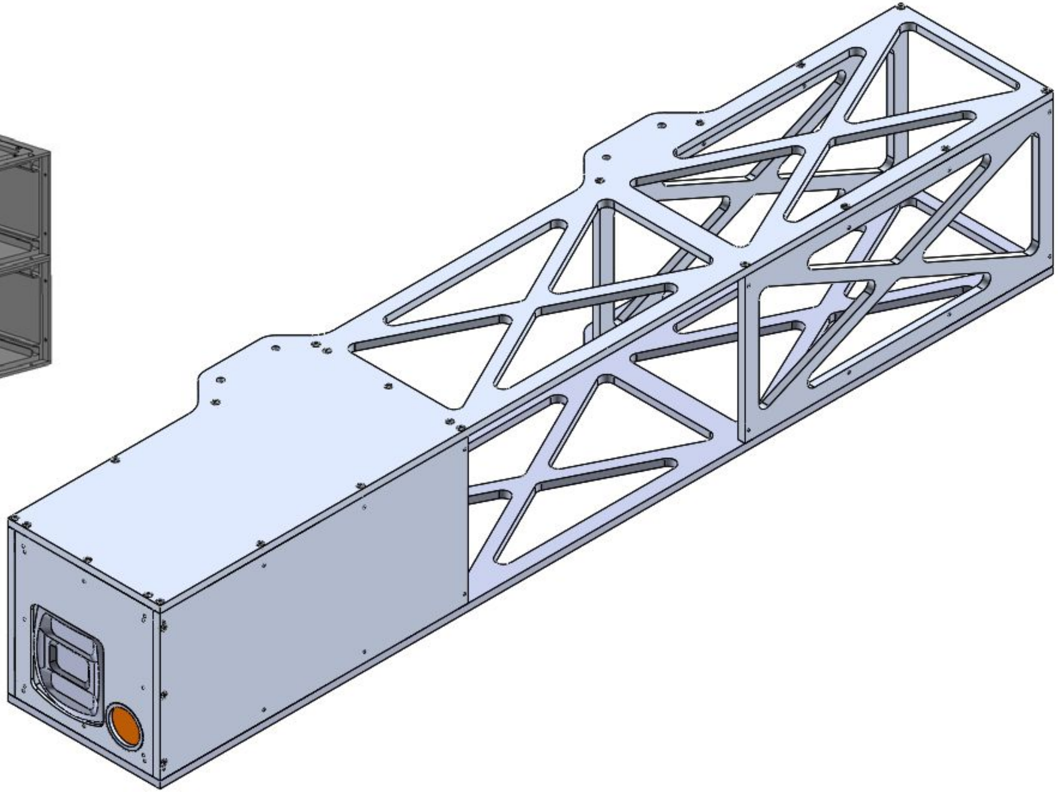
Drawing Number	Revision	Release Date	Description	Change Log:
0001	C	11/27/2018	This drawing calls out the same dimensions as the NR drawing 6EHC7 in order to show compliance with require DR.4.1-STR	11/19/2018 -> Initial Release 11/26/2018 -> NEW OPTICAL CAMERA MOUNTING FEATURES 11/27/2018 -> NEW FRONT PLATE MOUNTING FEATURES
0002	B	11/27/2018	Left plate of the main structure. This is the right plate when mounted in the SILO 1 position.	11/19/2018 -> Initial Release 11/27/2018 -> NEW FRONT PLATE MOUNTING FEATURES
0003	B	11/27/2018	Right plate of the main structure. This it the left plate when mounted in the SILO 1 position.	11/19/2018 -> Initial Release 11/27/2018 -> NEW FRONT PLATE MOUNTING FEATURES
0004	A	11/19/2018	Back plate of the main structure.	11/19/2018 -> Initial Release
0005	C	11/27/2018	Front plate of the main structure.	11/19/2018 -> Initial Release 11/26/2018 -> NEW OPTICAL CAMERA APERTURE 11/27/2018 -> NEW FRONT PLATE MOUNTING FEATURES
0006	B	11/27/2018	Base plate of the main structure. This is the top plate when mounted in the SILO 1 position.	11/19/2018 -> Initial Release 11/27/2018 -> NEW FRONT PLATE MOUNTING FEATURES

Mechanical Drawings (2)

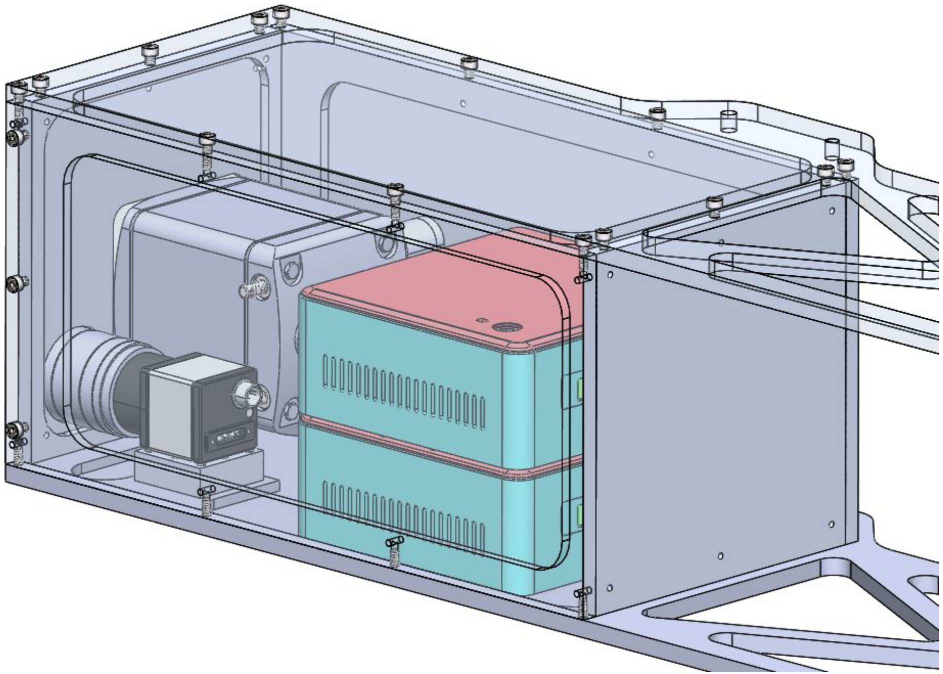
Drawing Number	Revision	Release Date	Description	Change Log:
0007	C	11/27/2018	Top plate of the main structure. This is the base plate when mounted in the SILO 1 position.	11/19/2018 -> Initial Release 11/26/2018 -> NEW OPTICAL CAMERA MOUNTING HOLES 11/27/2018 -> NEW FRONT PLATE MOUNTING FEATURES
0008	A	11/19/2018	Outer bulkhead of the main structure.	11/19/2018 -> Initial Release
0009	A	11/19/2018	Optical camera mounting block.	11/19/2018 -> Initial Release
0010	A	11/19/2018	TOF camera mounting block.	11/19/2018 -> Initial Release
0011	C	11/27/2018	VANTAGE assembly drawing including exploded views.	11/20/2018 -> Initial Release 11/26/2018 -> NEW OPTICAL CAMERA MOUNTING HOLES 11/27/2018 -> NEW FRONT PLATE MOUNTING FEATURES

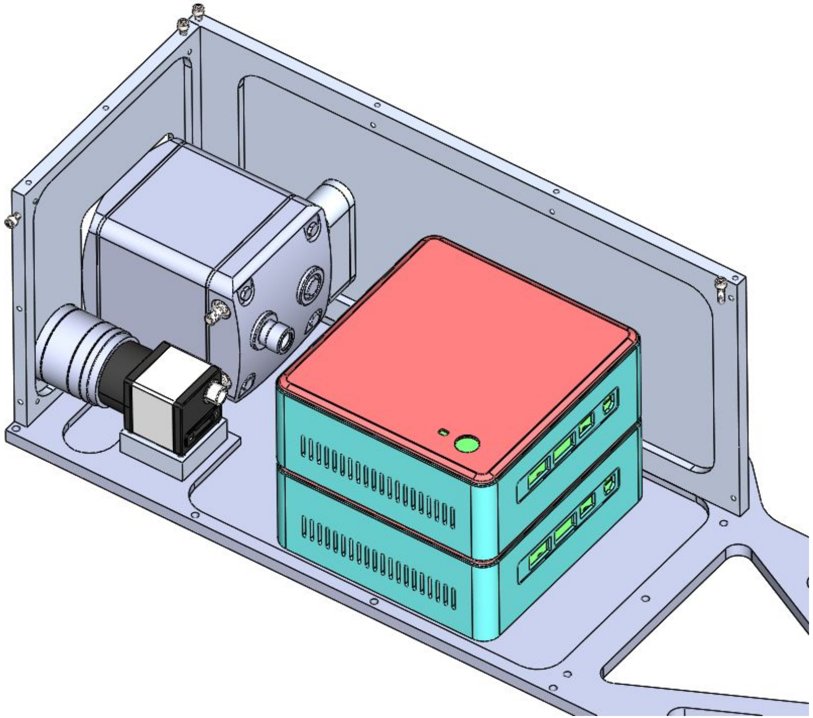
CAD Screen Captures





CAD Screen Captures





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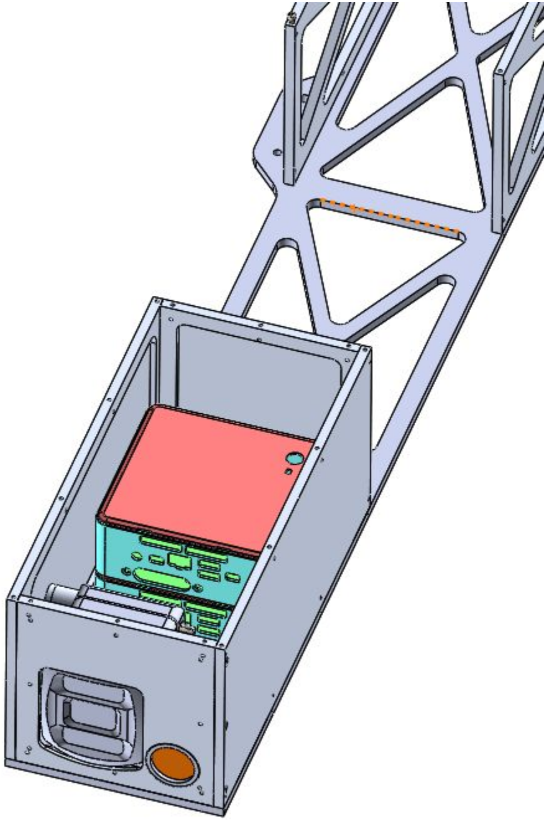

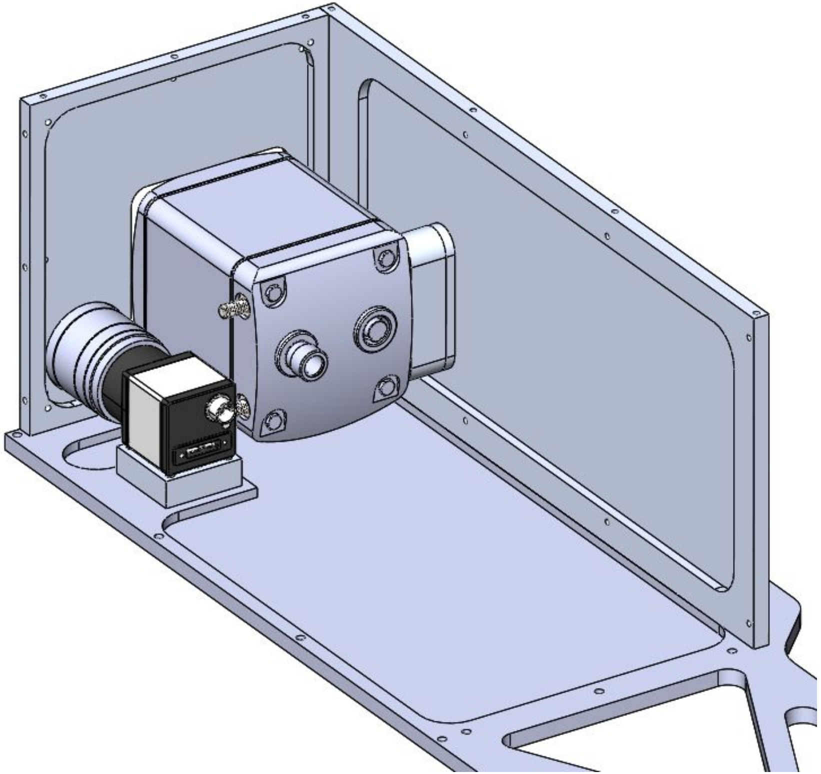

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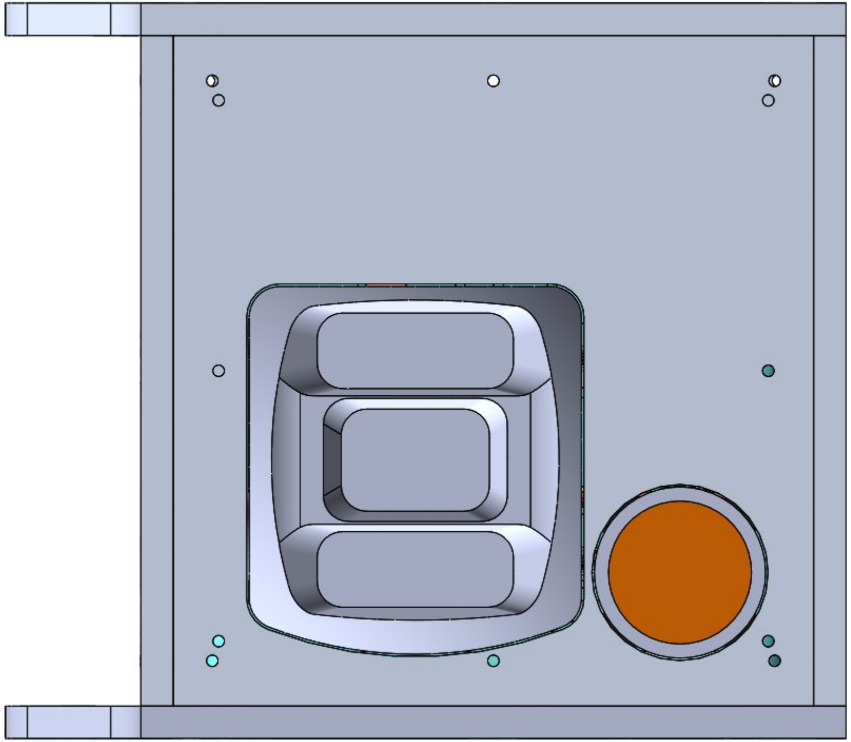

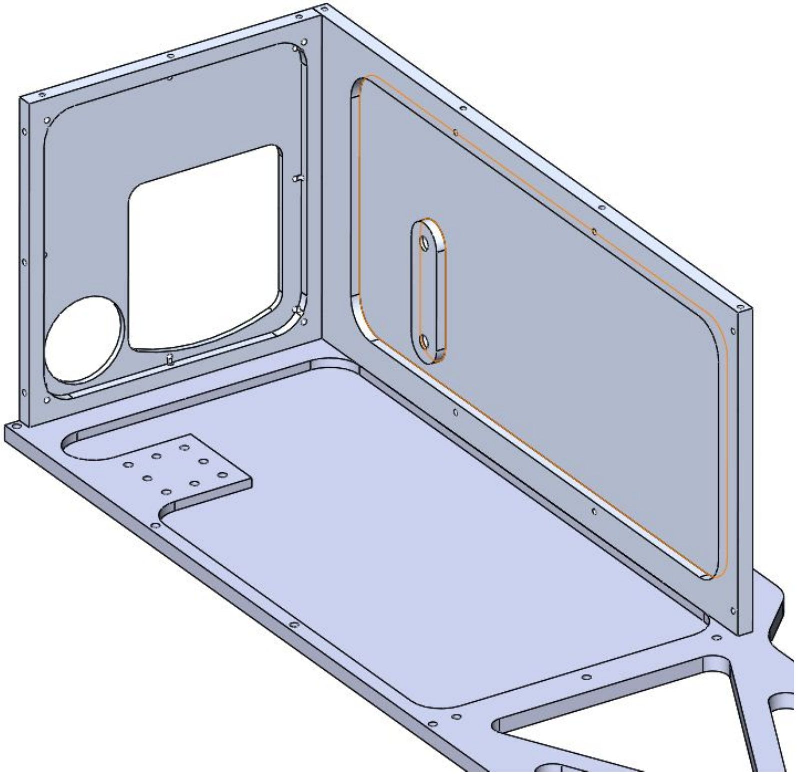

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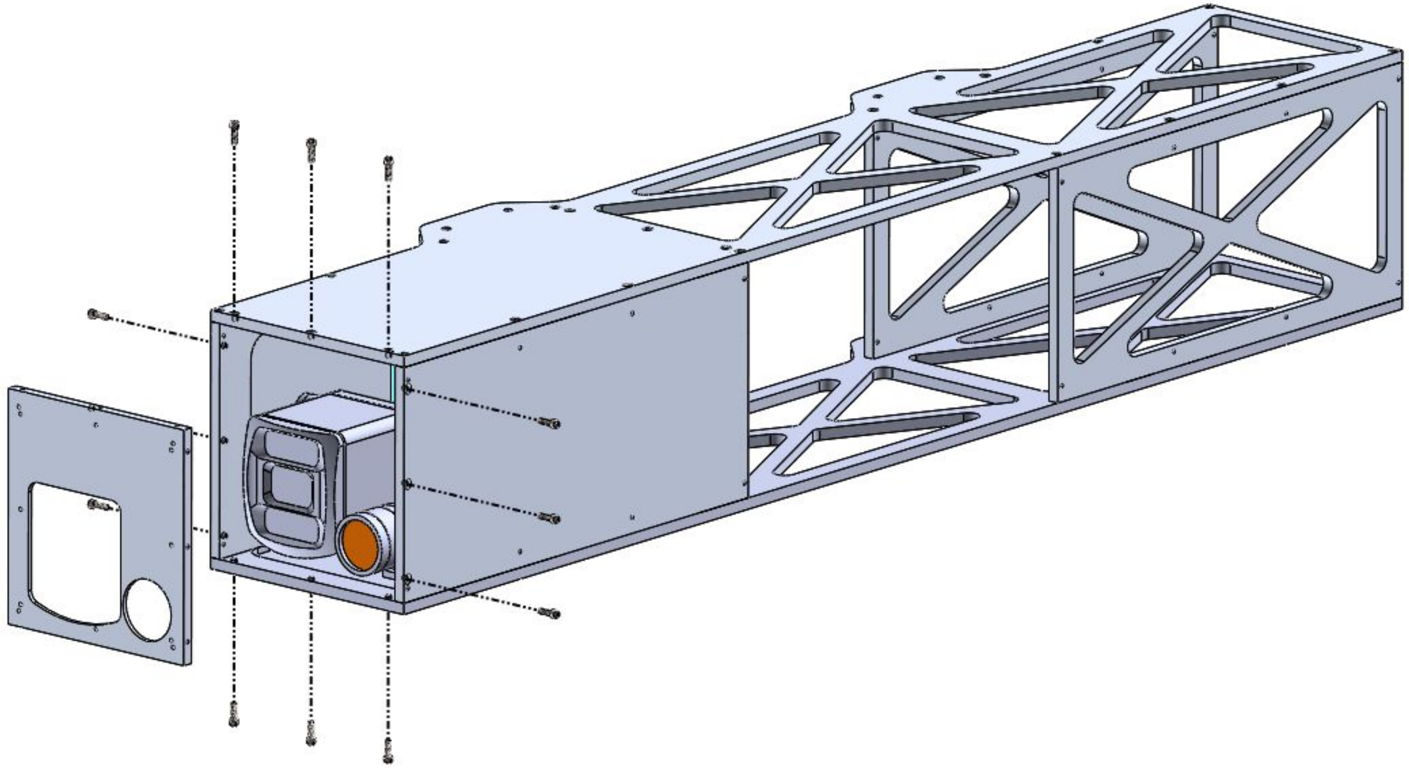
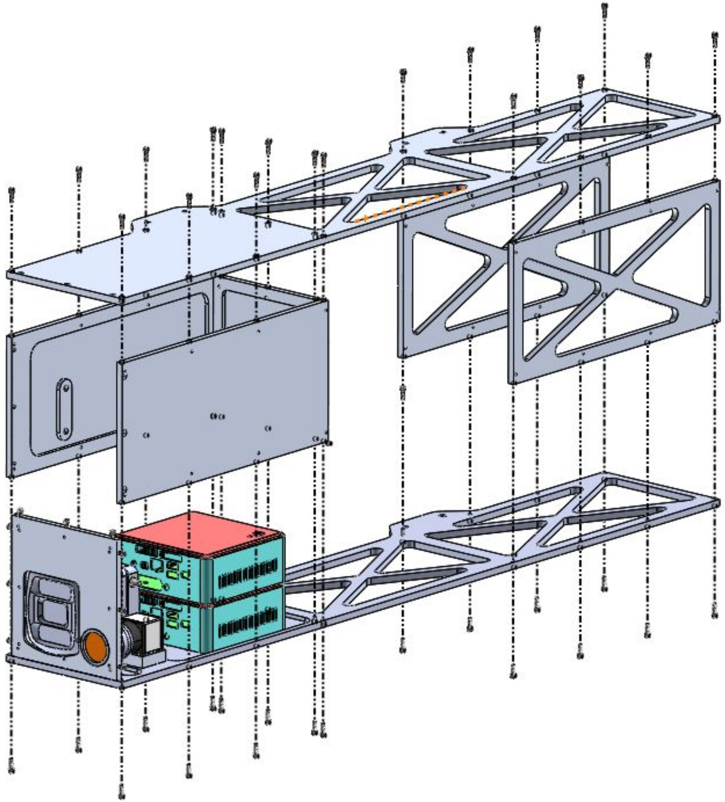
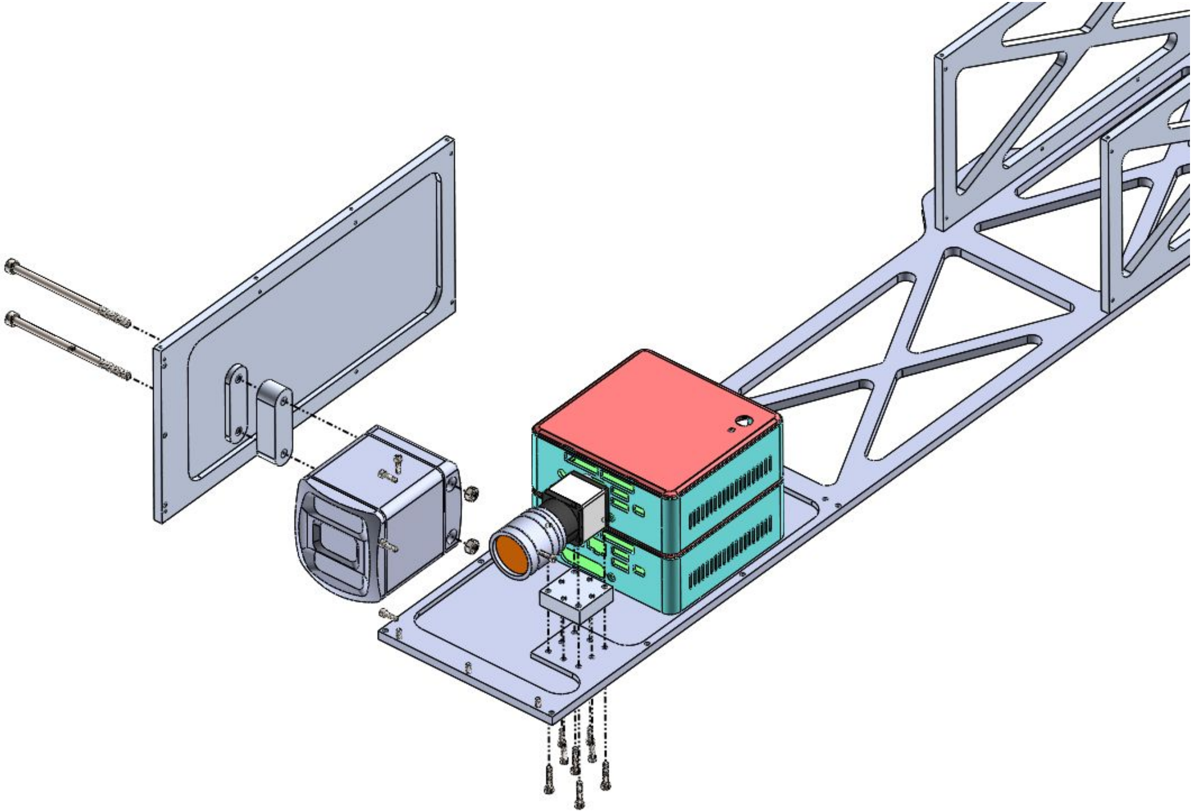


CAD Screen Captures



CAD Screen Captures



Testing Backup

Testing Requirements (1)

Req.	Description
DR.5.3-TST	The test rig shall be capable of simulating all required deployment scenarios including off nominal deployment cases and deployments from the 7 other Nanorack Deployer tubes not taken up by the VANTAGE system.
DR.5.3.1-TST	The test rig shall be able to produce mock cubesat motion at velocities between 0 and 3 m/s.

Req.	100m Test	Modular Test
DR.5.3-TST	• The position of the VANTAGE Flatsat in the 100m Test is variable and thus can be adjusted in relation to the Cubesat Kabob on the boom arm. The boom arm starting position is fixed. • The car is capable of moving at different speeds within the 1-3m/s range. • Cubesats are fixed to the Cubesat Kabob in prescribed orientations which can be arranged and designed as the deployment case requires. • Ref: Content Slides for Overview	• Mock CubeSat Cart is capable of mounting all required deployment scenarios. • Mock CubeSat Cart can simulate deployments from the 7 other NanoRacks Deployer tubes. • Nema 34 Motor is capable of producing off nominal velocity. • Off nominal deployment times/failures trivially simulated.
DR.5.3.1-TST	• The test rig is attached to a motor vehicle (BMW535i) which is capable of driving at steady speeds between 0 and 3m/s • Ref: 100M Test Mounting to Car	• The Nema 34 Motor is capable of accelerating the cart in its maximum weight scenario (2 2x3U mock CubeSats) to 3 m/s. • Ref: Motor Feasibility

Testing Requirements (2)

Req.	Description
DR.5.3.2-TST	The test rig shall be capable of mounting all required combinations of mock cubesats that are launched from the Nanorack Deployer.
DR.5.3.3-TST	The test rig shall be capable of mounting mock cubesats such that their geometric center is at the same height as the geometric center of VANTAGE, as well as at a height 5.732 in below the geometric center of VANTAGE.

Req.	100m Test	Modular Test
DR.5.3.2-TST	• The mock cubesats are designed in 1U, 2U, and 3U sizes based on the NanoRacks Interface Definition Document. • These are fixed to the Cubesat Kabob using a rail and pin system which allows for modularity and ease of changing order of deployment. • Ref: 100M Test Mounting to CubeSats	• The Mock CubeSat Cart is capable of mounting 6 1Us, 3 2Us, 2 3Us, 1 6U, 2 2x3Us, and any other possible combination that NanoRacks has launched in the past. • Ref: Mock CubeSat Cart
DR.5.3.3-TST	• VANTAGE TOF and optical camera are mounted on an arm connected to a tripod. The tripod location of the VANTAGE sensors is adjustable • Ref: VANTAGE Sensor Mounting	• The Mock CubeSat Cart can attach mock CubeSats with a 7.87 in pole as well as a 13.61 in one. This allows for mock CubeSats to be attached at the required heights. • Ref: Mock CubeSat Cart

Testing Requirements (3)

Req.	Description
DR.5.3.4-TST	The test rig shall be capable of mounting mock cubesats such that their geometric center is horizontally aligned with VANTAGE's geometric center, as well as 5.48 in, 15.748 in, and 21.228 in to the right of VANTAGE's geometric center.
DR.6.4-TST	The test rig shall produce truth data for relative position vectors accurate up to 1 cm 1σ to a distance of 10 m, changing to an accuracy of at least a hundredth of the range 1σ up to a distance of 100 m.

Req.	100m Test	Modular Test
DR.5.3.4-TST	• VANTAGE TOF and optical camera are mounted on an arm connected to a tripod. The tripod location of the VANTAGE sensors is adjustable • Ref: VANTAGE Sensor Mounting	• The Mock CubeSat Cart is capable of mounting mock CubeSats at all of these locations. • Ref: Mock CubeSat Cart
DR.6.4-TST	• GPS RTK data is generated for the 100m Test • Ref: GPS TRK System (2)	• Vicon System position error of 0.0775 mm. • Ref: RECUV Test Location

Testing Requirements (4)

Req.	Description
DR.6.5-TST	The test rig shall produce truth data for relative velocity vectors accurate up to 0.1 cm/s 1σ to a distance of 10 m, changing to an accuracy of 1 cm/s 1σ up to a distance of 100 m.
DR.1.5-TST	The test rig shall use a light source that produces a constant luminous flux of at least 1000 lumens on the surface of the mock cubesat.

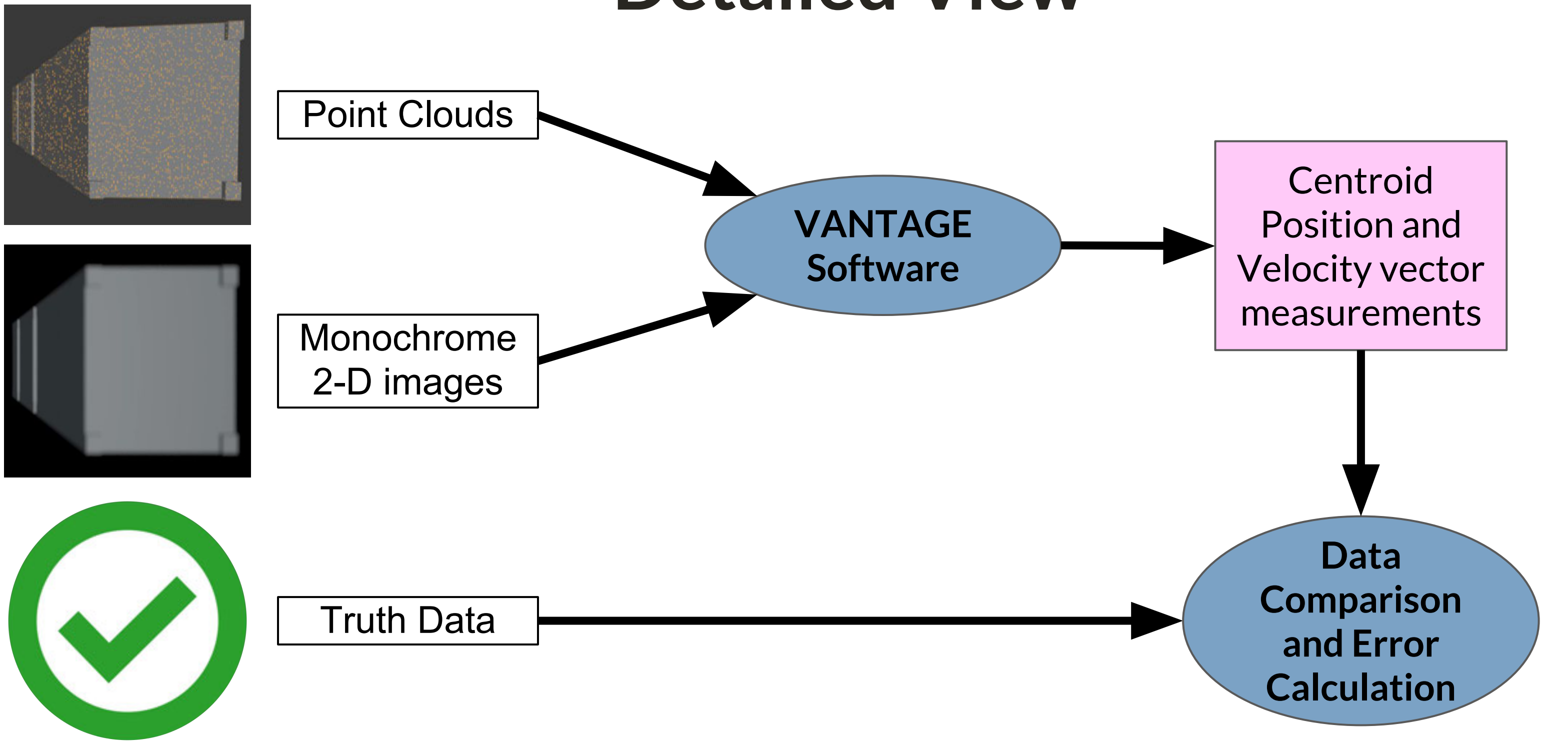
Req.	100m Test	Modular Test
DR.6.5-TST	• GPS RTK data is generated for the 100m Test • Ref: GPS TRK System (2)	• Vicon System velocity error of 0.0775 mm/s. • Ref: RECUV Test Location
DR.1.5-TST	• A flashlight has been chosen that produces 10x the required illumination • The flashlight will be mounted to the vehicle and pointed at the mock cubesats during the test to produce the required illuminance of the mock cubesats • The same flashlight is used for both the 100m test and the Modular test • Ref: Simulating Ideal Lighting	• The same flashlight that will be used for the 100m Test will be used for the Modular Test as well. • The flashlight will be mounted to the VANTAGE Shelf and will provide effectively constant illumination over the short range. • Can be mounted to the cart as well. • Ref: Simulating Ideal Lighting

Testing FR Satisfaction

FR	FR. Summary	Simulation Test	Modular Test*	100m Test**	Test Summary
FR.1	Images of Mock CubeSats between 3 and 100 m		✓	✓	Modular and 100m Tests move cubesats at speeds in this range
FR.2	Receive and interpret commands	✓	✓	✓	All Tests can verify this
FR.3	Accept power			✓	100m Test will run with NanoRacks provided power on the final run in order to minimize risk of hardware damage
FR.4	Mechanical Integration	✓		✓	This is a separate integration test with the mechanical structure and NanoRacks ground based hardware
FR.5	Detect and track Mock CubeSats between 3 and 100m	✓	✓	✓	All Test can verify this
FR.6	Estimate position and velocity vector of Mock CubeSats	✓	✓	✓	VANTAGE is the test article in all three Tests
FR.7	Off nominal deployment cases	✓	✓		Simulation and Modular Tests will verify this
FR.8	Reporting data back to user	✓	✓	✓	All three Tests can verify this

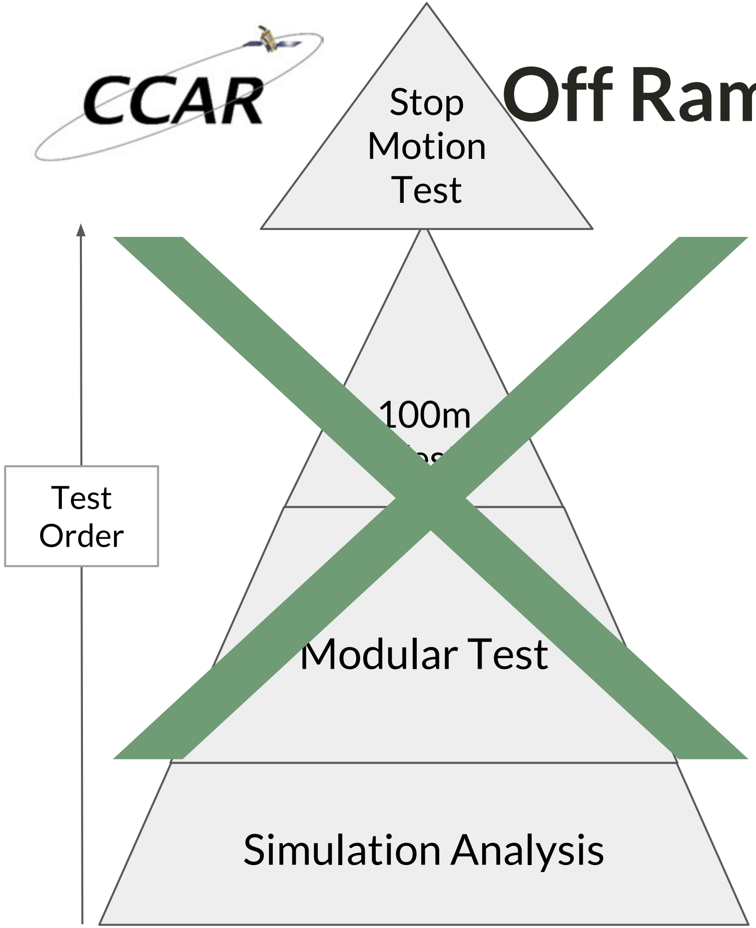
*Real world sensor data produced
**Real world sensor data produced + beginning to end system verification

Requirement Verification Plan Detailed View



Stop Motion Test Backup

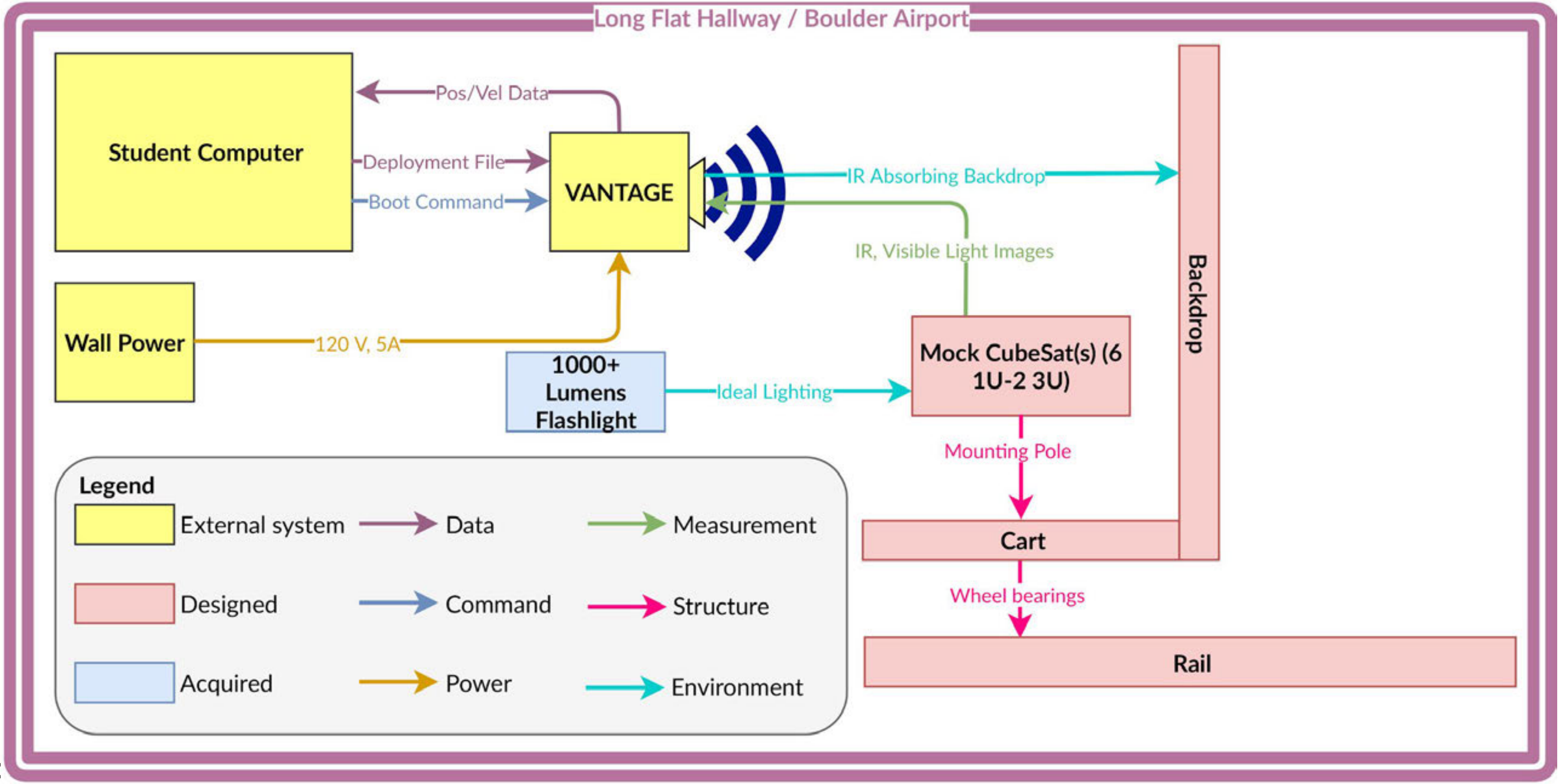
Off Ramp Stop Motion Test



Functional Req.	Summary	Simulation Test	Stop Motion Test*
FR.1	Images of Mock CubeSats between 3 and 100 m		✓
FR.2	Receive and interpret commands	✓	✓
FR.3	Accept NanoRacks DC power		✓
FR.5	Detect and track Mock CubeSats between 3 and 100m	✓	✓
FR.6	Estimate position and velocity vector of Mock CubeSats	✓	✓
FR.7	Off nominal deployment cases	✓	✓
FR.8	Reporting data back to user	✓	✓

*Real world sensor data produced + beginning to end system verification

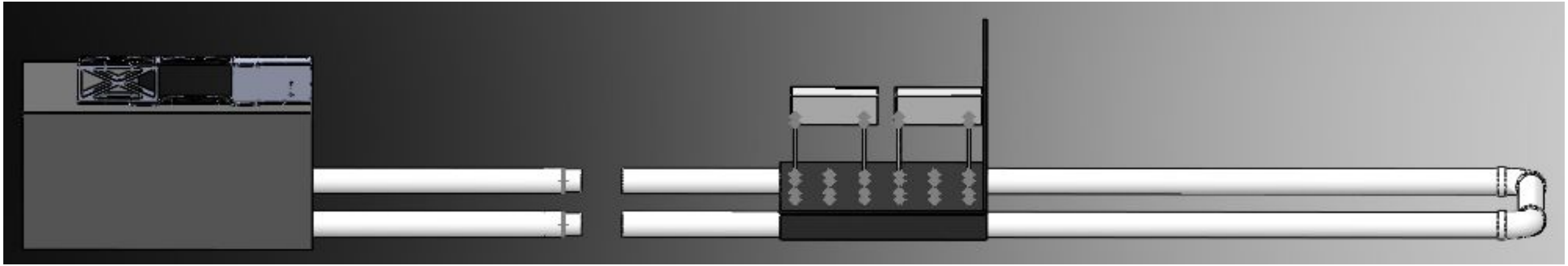
Stop Motion Test FBD



Stop Motion Test Overview

Necessary Capability/ Measurement	Hardware Used	Hardware Capability	Relevant Requirements
Truth Data **(Position & Velocity)**	Recorded cart position	Ruler provides **1 mm** accuracy	**DR.6.1:** Position Accuracy (**10 cm** for 3-10 10m ,10% of range to 100 m). **DR.6.2:** Velocity Accuracy (**1 cm/s** to 10 m , 10cm/s to 100m)
Test Data **(Position & Velocity)**	TOF & Optical Camera (**Unit Under Test**)	N/A	**DR.6.1** & **DR.6.2**
Imaging Targets	Mock CubeSat Models	Simulates the appearance of a CubeSat	**FR.1: Images** of Mock CubeSats
Various Deployment Scenarios	Mock CubeSat Cart	Capable of mounting all deployment scenarios	**FR.5:** Mount up to **6 1U to 2 3U** Mock CubeSats
Mock CubeSat Motion	N/A	N/A	**FR.6, FR.7:** Mock Cubesats move with velocities between **0 and 3 [m/s]**.

Stop Motion Test Setup



Procedure

1. Cart will we positioned at start location.
2. Based on the FPS of each sensor, cart will be incrementally moved
   a. If doing for 100 m, re-assemble rail every 10 m
3. Data will be captured at each location and tagged with a timestamp
4. Once all data collected, fed into software system

100 m Test Backup

100 m Test PDD Req. and Off Ramps

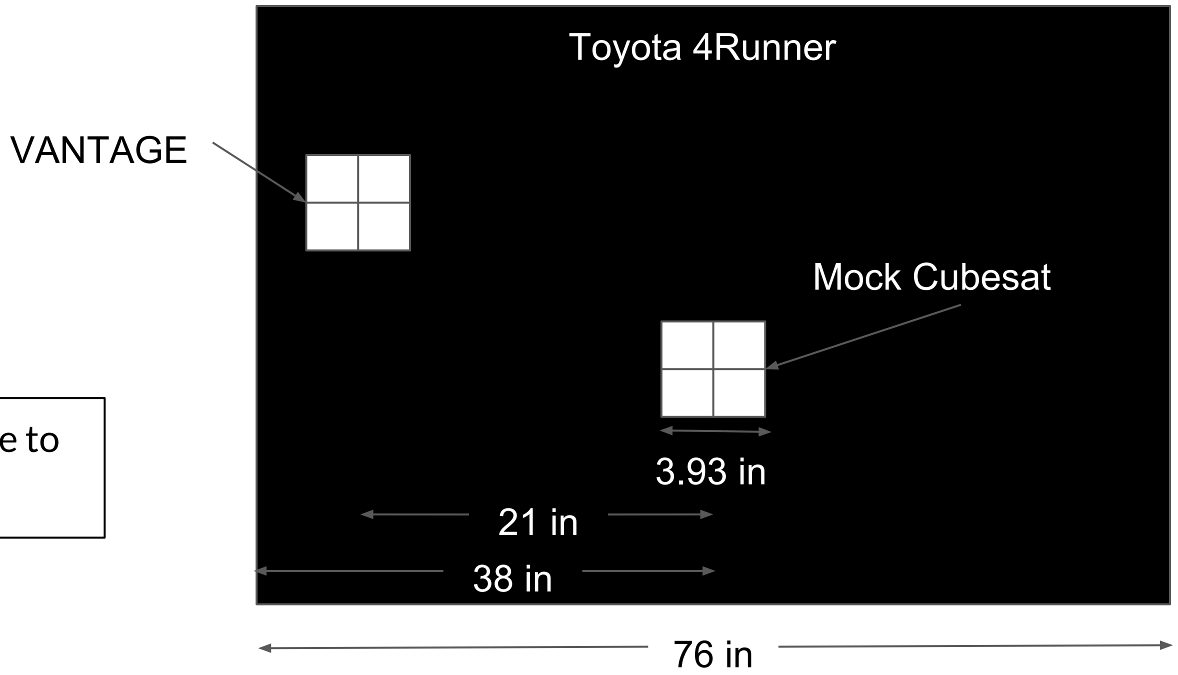
- Per the PDD and requirements:
  - 8 testing specific requirements that cover
    - Test rig capability to simulate different cubesat configurations
    - Truth data for position and velocity relative to the VANTAGE system
    - Ideal lighting assumptions

- Acceptable off ramps:
  - Stop motion capture
    - No live motion, truth data can be acquired using simple measurement tools
    - Remove need to purchase, build, troubleshoot, and verify any motion related components
    - Stitch all pictures together and feed that into VANTAGE software
  - Verify by simulation
    - Use Blensor simulation to create a data set which is then fed into VANTAGE
    - Perfect truth data, but less realistic sensor inputs

Trade on Car Back Mount

For furthest tube test case:

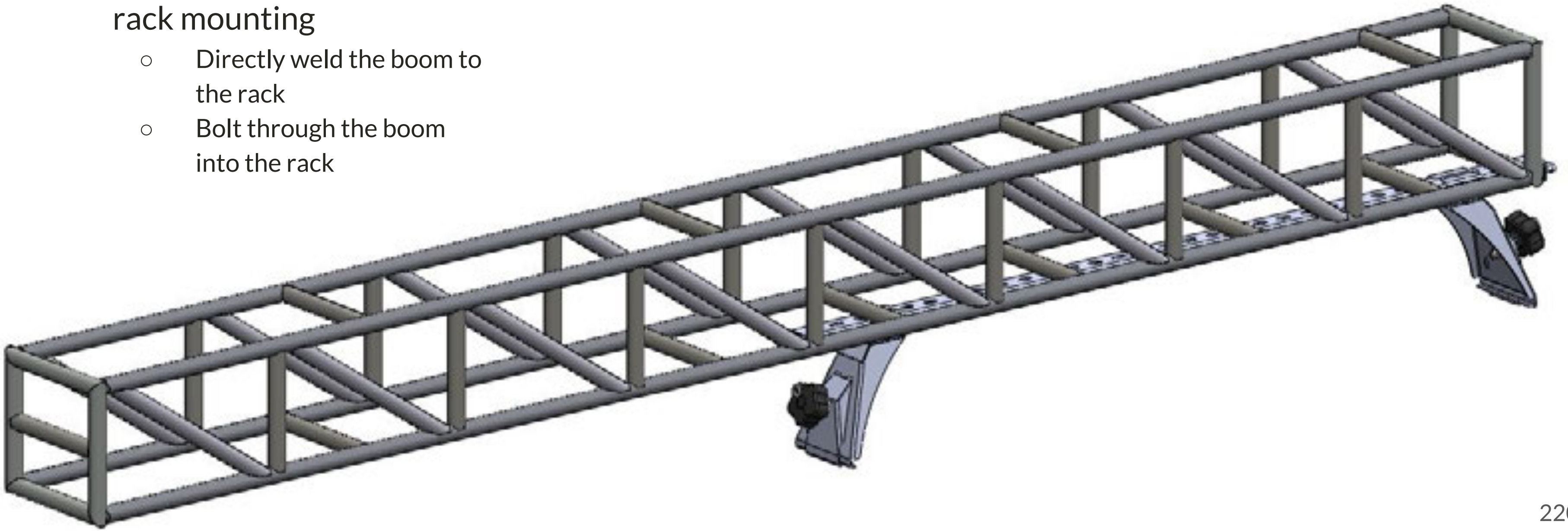
- Distance between VANTAGE and tube is 21.228 in.



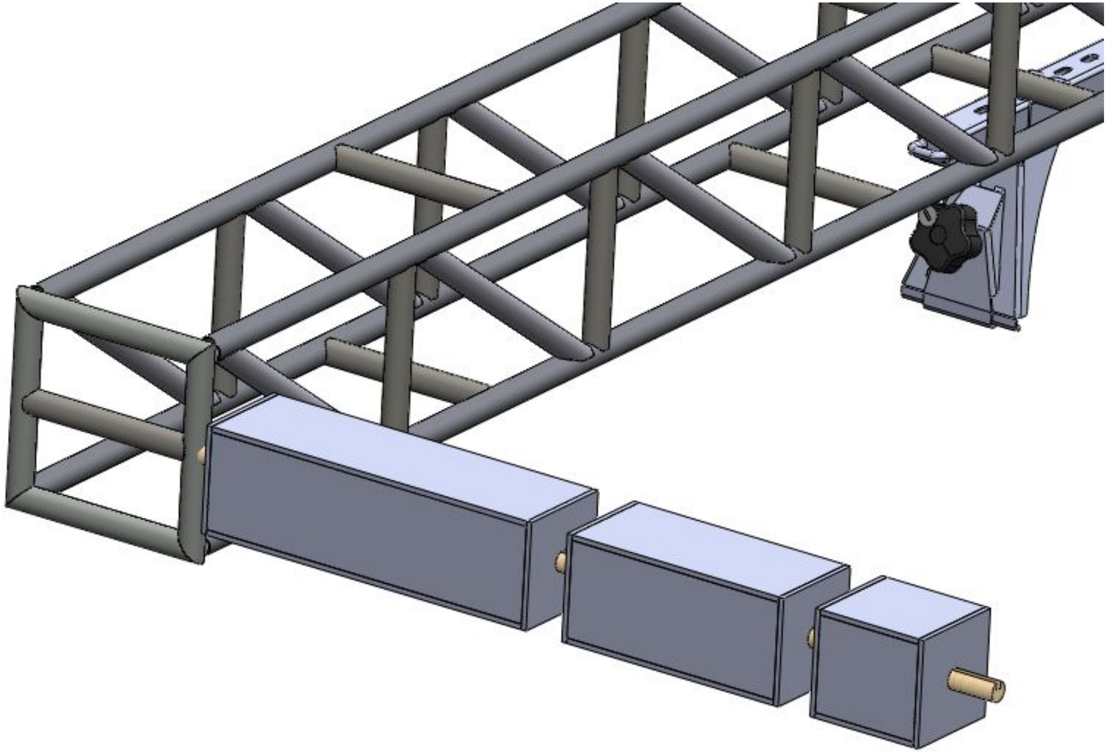
Problem: VANTAGE will have to start directly behind the car

100m Test Mounting to Car

- Rack is COTS part made for the test vehicle
- Two options for boom to rack mounting
  - Directly weld the boom to the rack
  - Bolt through the boom into the rack



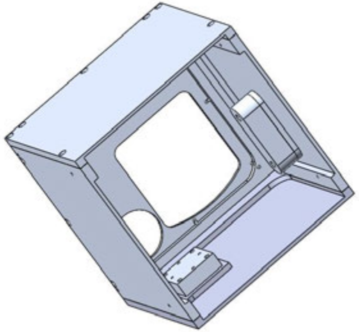
100m Test Mounting to CubeSats

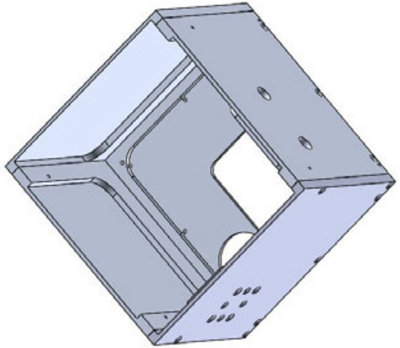


- Cubesats lock into groove of the Cubesat Kabob to prevent rotation
- Cubesats can be locked from translation by adding a pin to either side through the rod
  - This pin can be as simple as a paperclip
- Cubesat Kabob is simply bolted with two bolts and wing nuts to the boom

VANTAGE Sensor Mounting

- For the 100m Test
  - VANTAGE sensors will be mounted to a 3D printed part that will replicate the mounting features
  - The 3D printed part will be clamped to the underside of the boom to prevent an unstable pendulum from being formed
  - A counter weight will be applied to the other end of the boom to balance the mass of the VANTAGE sensor testing mount
  - The tripod height and position can be adjusted relative to the car to ensure that deployments come from the “correct” position





Steel Material Properties

Table 2.2.1.0(b). Design Mechanical and Physical Properties of AISI 1025 Carbon Steel

Specification	AMS 5046 and AMS-S-7952	AMS 5075, AMS 5077 and AMS-T-5066[a]	ASTM A 108
Form	Sheet, strip, and plate	Tubing	Bar
Condition	Annealed	Normalized	All
Thickness, in.	...	...	...
Basis	S	S	S[b]
Mechanical Properties:			
F_{tu}, ksi:			
L	55	55	55
LT	55	55	55
ST	...	...	55
F_{ty}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{cy}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{su}, ksi	35	35	35
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	90	90	90
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent:			
L	...	c	c
LT	c	...	...
E, 10^3 ksi		29.0	
E_c, 10^3 ksi		29.0	
G, 10^3 ksi		11.0	
μ		0.32	
Physical Properties:			
ω, lb/in.^{3}		0.284	
C, Btu/(lb)(°F)		0.116 (122 to 212°F)	
K, Btu/[(hr)(ft^2)(°F)/ft]		30.0 (at 32°F)	
α, 10^{-6} in./in./°F		See Figure 2.2.1.0	

Table 2.5.1.0(c). Design Mechanical and Physical Properties of 280 Maraging Steel

Specification	AMS 6521[a]			AMS 6514	
Form	Sheet	Plate		Bar	
Condition	Maraged at 900°F			Maraged at 900°F	
Thickness or diameter, in.	≤0.187	0.188-0.250	>0.250	<4.000	4.000-10.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	271	276	...	280	275
T	280	280	280	280	275
F_{ty}, ksi:					
L	262	267	...	270	270
T	270	270	270	270	270
F_{cy}, ksi:					
L	244	...	...	281	...
T	248	281	...	...	...
F_{su}, ksi	163	170	...	162	...
F_{bru}, ksi:					
(e/D = 1.5)	359	386	...	...	...
(e/D = 2.0)	487	492	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	306	357	...	...	...
(e/D = 2.0)	389	390	...	...	...
e, percent:					
L	...[b]	...[b]	...[b]	5	4
T				4	2
RA, percent:					
L	...	...	...	30	25
T	...	...	...	25	20
E, 10^3 ksi			26.5		
E_c, 10^3 ksi:					
L			28.6		
T			29.6		
)^3 ksi			...		
			0.31		
al Properties:					
/in.^{3}			0.286		
and α			See Figure 2.5.1.0		

MMPDS-01

31 January 2003

Beam Analysis Summary

Quantity	Value
Predicted deflection at the tip	<1mm
Safety Factor on yield due to curvature	169
Buckling Safety Factor	257
Safety Factor on bolt experiencing reaction moment	200
First fundamental frequency	51Hz

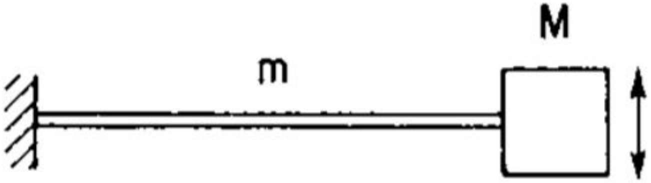
It should be noted that this analysis only assumes the longerons are part of the beam. All of the battens and diagonals will increase stiffness and distributing loads pushing all of these number upward

Beam Analysis Formulas

CHAPTER 7

VIBRATION OF SYSTEMS HAVING DISTRIBUTED MASS AND ELASTICITY

William F. Stokey



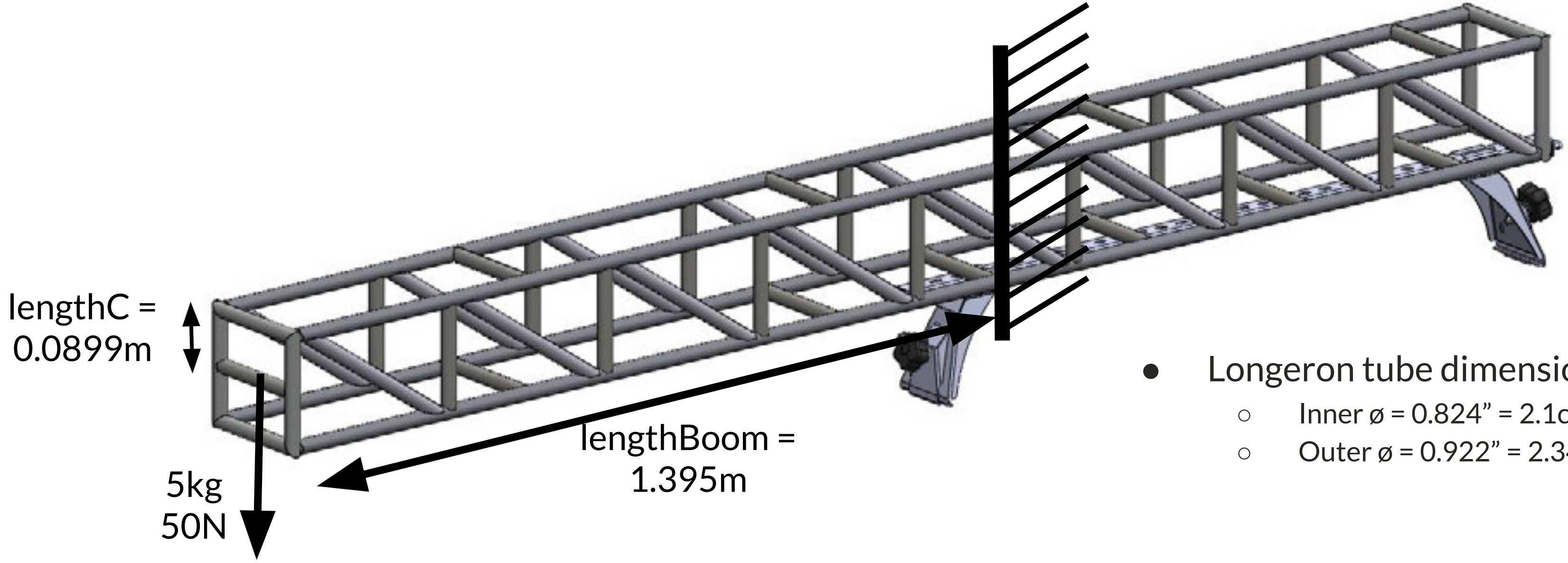
UNIFORM CANTILEVER BEAM WITH MASS ON END	$\sqrt{\dfrac{k}{M+0.23m}}$	$k = \dfrac{3EI}{l^3}$ l = BEAM LENGTH I = MOMENT OF INERTIA

Beam Analysis (1)

- Reasons a simple analysis of the long beam members is valid
  - Cross members (diagonals and battens) only add stiffness to the beam reducing displacements and raising modal frequencies
  - Rigid mounting in practice is on more of the beam surface than in the assumptions
  - Movement speeds will by under 2m/s (5mph)
  - *BMW suspension* on flat, smooth asphalt surface will dampen high percentage of road vibrations
  - Boom is essentially a completely rigid structure since all members are welded together
- Assumptions made in analysis
  - Consider the boom to be a beam made of only the “longerons” (8ft sections)
  - Consider the beam is cantilevered with the Cubesat Kabob end as the free end
  - The Cubesat Kabob provides only a downward force at the free end
  - This is a 1 DOF system
- Some numbers
  - Cubesat Kabob mass: SW says 2.28kg → Analysis uses 5kg
  - Carbon Steel Young’s Modulus E = 29e3ksi = 200GPa
  - Carbon Steel Yield Strength = 55ksi = 380MPa
  - Alloy Steel Yield Strength = 170ksi = 1172MPa

Beam Analysis (2)

- Layout of the boom dimensions
- All calculations done in SI units



- Longeron tube dimensions
  - Inner ø = 0.824” = 2.1cm
  - Outer ø = 0.922” = 2.34cm

Beam Analysis (3)

Calculate the second moment of area of the cross section using the parallel axis theorem

A single longeron centered crossection

```
I1 = π/4 (outerR^4 - innerR^4)
```

5.34564 × 10^-9

The distance of each longeron from the center of the beam crossection

```
distance = lengthC; (*(lengthC^2+lengthC^2)^0.5;*)
```

The area of a single longeron crossection

```
A = π (outerR^2 - innerR^2);
```

Parallel Axis theorem for second moments of area

```
I2 = I1 + A * distance^2;
```

The final second moment of area for the beam made of four longerons each at the same distance away from the beam center

```
Ibeam = 4 * I2
```

2.82369 × 10^-6

Galvanized steel pipe 3/4”

```
outerD = 0.0234188; (*m*) (*0.922"*)
innerD = 0.0209296; (*0.824"*)
outerR = outerD / 2;
innerR = innerD / 2;
```

CCAR

Beam Analysis (4)

VANTAGE

Considering the beam to be cantilevered we calculate the displacement at the tip

For a cantilevered beam: $F = \frac{3EI}{L^3} u$ or $u = \frac{FL^3}{3EI}$ and the force at the end is given by

```
F = Mass * g;
```

Thus the tip displacement is:

$$\text{Utip} = \frac{F * \text{lengthBoom}^3}{3 * \text{Esteel} * \text{Ibeam}}$$

0.0000785946

Calculate the maximum moment

$$\text{Mmax} = F * \text{lengthBoom}$$

68.4248

Calculate the maximum curvature

$$\kappa = \frac{\text{Mmax}}{\text{Esteel} * \text{Ibeam}}$$

0.000121162

Maximum strain due to curvature

$$\epsilon = \kappa * \text{distance} \; (* \left(\text{distance} + \frac{\text{outerD}}{2}\right) *)$$

0.0000108913

Maximum stress due to curvature

$$\sigma = \text{Esteel} * \epsilon$$

2.17826×10^6

The safety factor on the yield stress of steel

$$\text{SF} = \frac{\sigma\text{yield}}{\sigma}$$

169.86

Beam Buckling Analysis

Buckling Analysis

longest member length

```
lmember = .328;
```

Buckling load

$$P = \frac{\pi^2 \, Esteel \star I1}{lmember^2}$$

98 080.3

Compression load caused by moment in a single bar

```
M = F * lengthBoom;
```

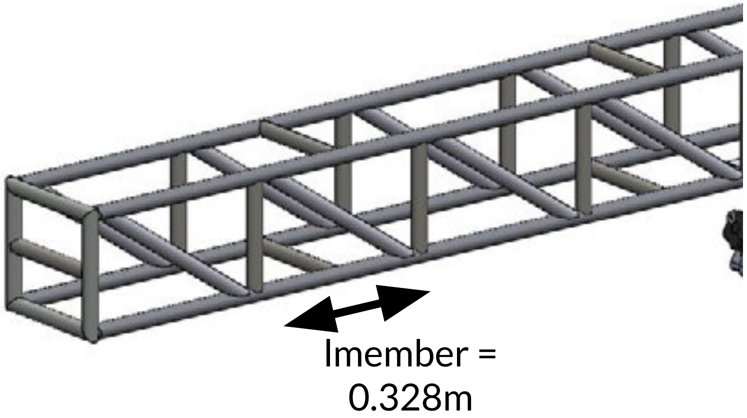
$$Fbar = \frac{M / lengthC}{2}$$

380.6

Buckling safety factor

$$SFbuckling = \frac{P}{Fbar}$$

257.699



Beam Modal Analysis

Modal Analysis of the cantilever boom

More beam characteristics

```
rodmass = 1.65;
rodlength = 2.42;
ρ = 4 * rodmass / rodlength; (*four rods*)
```

Modeled as a cantilever with non negligible boom mass and end mass

$$f1 = \frac{1}{2\pi}\sqrt{\frac{3 * Esteel * Ibeam}{(0.233 * \rho * lengthBoom + Mass) * lengthBoom^3}}$$

51.8222

Pin Fastener Analysis

Cantilevered Pinned Beam analysis

```
TSalloysteel = 1172000000;
massBoom = 15;
TotallengthBoom = 3.05;
Dscrew = 0.006;
Rscrew = Dscrew / 2;
```

$$\text{Ascrew} = \pi \star \text{Rscrew}^2;$$

Maximum force on the screw

```
TotalMass = massBoom + Mass;
CounterMoment = TotalMass * g * lengthBoom;
```

$$\text{ForceScrew} = \frac{\text{CounterMoment}}{\text{TotallengthBoom} - \text{lengthBoom}}$$

165.377

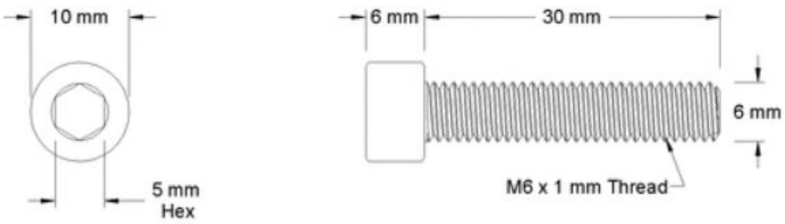
Tensile stress on the screw

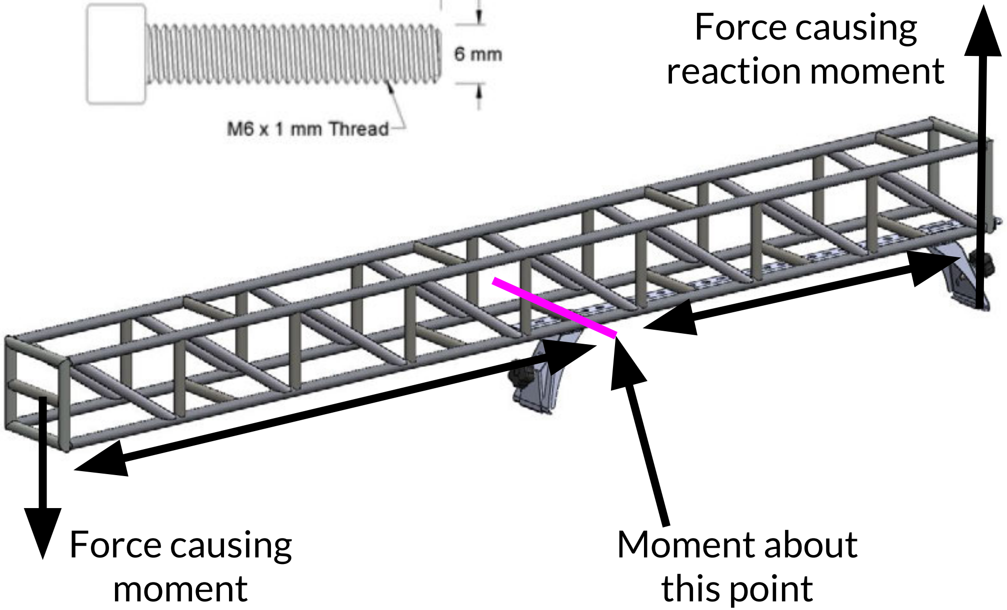
$$\sigma\text{screw} = \frac{\text{ForceScrew}}{\text{Ascrew}}$$

5.84902×10^6

$$\text{FSscrew} = \frac{\text{TSalloysteel}}{\sigma\text{screw}}$$

200.376





100m Test Manufacturing Plan (1)

- Built all boom components
  - Boom components should be cut to the mechanical specifications outlined in the mechanical drawings
  - The thin steel pipe is easily cut with a bandsaw or miter saw, edges can be deburred with a simple grinder
- Dry fit all boom components
  - Using tape, all the boom components can be dry-fit together to make sure that they are properly sized to begin welding
  - The dry-fit will allow for small adjustments to be made as required
- Dry fit car rack
  - This will be a simple test of the purchased car rack with the planned test vehicle
- Boom construction
  - Welding the components of the boom will be done by stick welding. There is no need for more precise or cleaner welds
  - Order of welding will take place according to the welding procedures detailed in the Test Boom Construction document
- Modify car rack to interface with boom
  - Once the boom has been completed, its segments will be fixed which includes the mounting features which connect the boom to the car rack
  - If the car rack can be welded (the current model is also steel) the the boom will just be welded to the car rack
  - If the car rack cannot be welded then the rack will be modified with bolt holes to connect the boom directly to the rack

100m Test Manufacturing Plan (3)

- Schedule
  - Pending full design approval the plan is to initiate manufacture over Winter Break (estimate roughly 5 days)
    - Boom component crafting expected to take 8hrs
    - Boom dry fit and small mods expected to take 8hrs
    - Boom welding expected to take 8hrs
    - Cubesat kabob manufacture (can be run in parallel) expected to take 8hrs
    - Full system fit and necessary modifications expected to take 8rhs
  - Worst case is that no welding resources are available over Winter Break
    - This only requires welding time to be taken once Spring semester starts
    - This pushes back the full system fit check and adjustments

100m Test Material and Costs

- Link to BOM Document
- Largest expense is the roof rack for the vehicle
- Without the roof rack the total cost of materials is ~$168.73

Part	Description	Source	QTY	Unit Cost	Part Cost	Notes
Mounting	Conduit Clamp	https://www	8	0.83	6.64	Need 6 plus buy 2 extra for a total of 8
BMW Roof Rack	Modified Roof Rack for mounting	https://www	1	139.95	139.95	Only 4 left in stock, made of steel so thats good
Long Bars	10ft Pipe basically	https://www	4	6.2	24.8	
End Corner	For making the End Caps	https://www	8	0.42	3.36	
Studs	Short bars for the boom	https://www	10	0.35	3.5	
Long Cross Beam	Long cross beams for the boom	https://www	6	6.2	37.2	
Stick Welding Sticks	For welding the Boom	https://www	3	12.57	37.71	Buying more that we could possibly ever need
Mounting Bolts	Bolts from boom to rack and from boom to cubesat assembly	https://www	1	10.65	10.65	something beefy to hold the boom to the rack and the cubesats to the boom
Mounting Bolts Nuts	Nuts for the mounting bolts	https://www	1	10.94	10.94	need to make sure the bolts actually have an attachment mechanism
Cubesat rod	Rod for Cubesat Assembly	https://www	1	4.24	4.24	
Light Source	LED Spotlight	https://www	1	29.69	29.69	6000lm, out to 800m, 9000mAh battery rechargable through USB
					0	
					0	
					0	
					0	
					0	
					0	
Totals					308.68	

100m Test Manufacturing Plan (2)

- Manufacture the Cubesat Kabob
  - This will hold different CubeSat configurations for testing
  - CubeSat models will be 3D printed and attached to the CubeSat rod which is designed for easy switching between configs
- Full mechanical test fit
  - The boom and rack assembly will be joined with the car and then the CubeSat Kabob will be mounted
  - A short driving test will be conducted to ensure that no mounting issues have arisen

- Facilities and tool availability
  - Some shop access during winter break, best availability likely in early January prior to Spring semester
  - Personal welding equipment available
  - Personal equipment available to do all boom component creation and dry-fit without need for CU or professional facilities
- Fumes from galvanized steel welding and the approach for safety
  - Well ventilated area or masks would be required during the welding of the boom components since stock is galvanized electrical conduit piping
- Welding experience
  - 2 members on the team have prior welding experience
  - Stick welding is quick and simple, time estimate to complete welding is a single day

100m Test Mechanical Drawings

- Please see the table below for descriptions of each drawing
- The PDFs can be found in this FOLDER and are also printed for the convenience of the reviewers

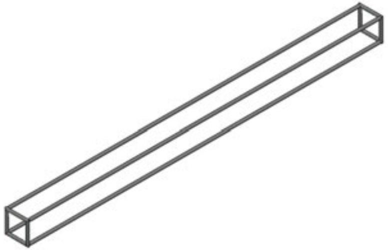
Drawing Number	Revision	Release Date	Description	Change Log:
0000	A	11/24/2018	Boom Assembly Drawing	11/24/2018 -> Initial Release
0001	A	11/24/2018	End Square Assembly Drawing	11/24/2018 -> Initial Release
0002	A	11/24/2018	End Corner Mechanical Drawing	11/24/2018 -> Initial Release
0003	A	11/24/2018	Stud Mechanical Drawing	11/24/2018 -> Initial Release
0004	A	11/24/2018	Long Cross Beam Mechanical Drawing	11/24/2018 -> Initial Release
0005	A	11/24/2018	Long Bar Mechanical Drawing	11/24/2018 -> Initial Release
0006	A	11/26/2018	Beam Cross-Section	11/26/2018 -> Initial Release

100m Test Boom Construction

- This list is a summary of the assembly procedures document which can be found HERE
- 1. Build the two Square End Caps per assembly drawing #0001
- 2. Connect the two Square End Caps with the four Long Bar components
- 3. Add the main studs to the structure based on the locations detailed in drawing #0000
- 4. Add the long cross beams to the near side
- 5. Add the long cross beams to the far side
- 6. Add the long cross beams to the top and bottom
- 7. Add the rack mounting studs
- 8. Add the Cubesat mounting stud
- 9. Add all mounting clamps and tighten to the Boom
- 10. Do a dry fit and mark locations of the mounting lamps
- 11. Weld mounting clamps into place for total rigid mounting

100m Test Boom Construction

1.



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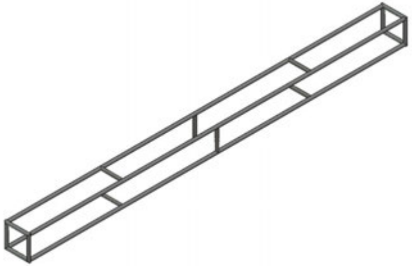

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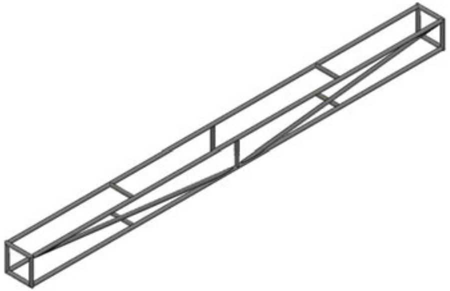

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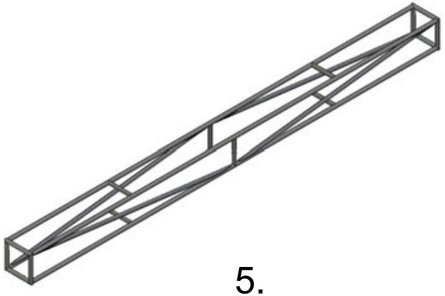

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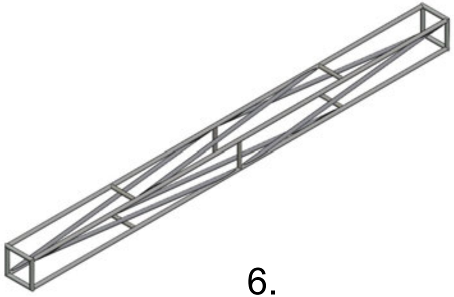

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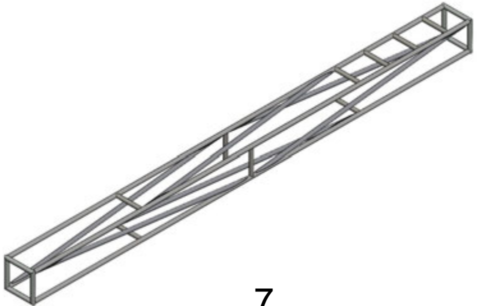


7.

GPS RTK System (1)

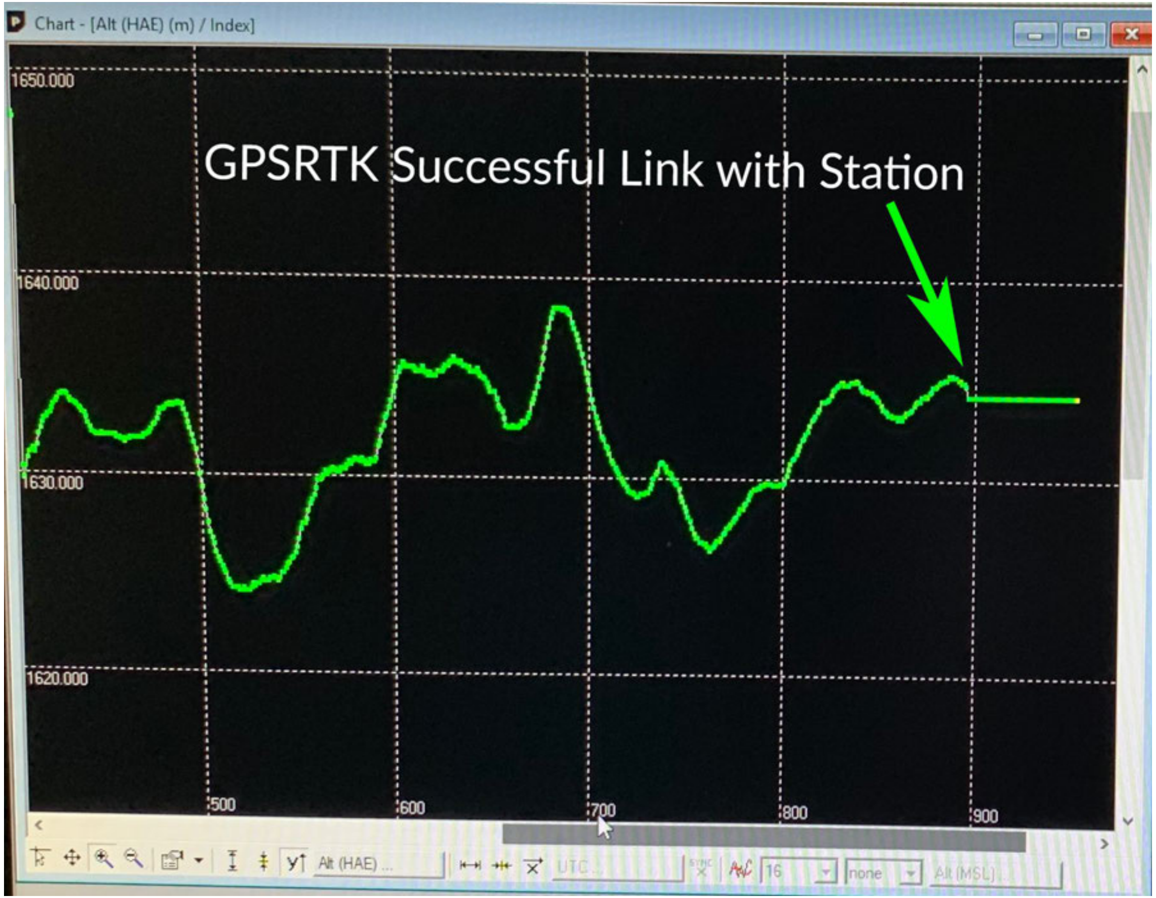
- Feasibility and System Familiarity
  - We have interfaced with the UBlox C94-M8P GPS RTK receivers and software
  - Found some documentation and identified some potential paths forward
- Issues
  - Software driver issues encountered initially
  - Plan to troubleshoot and update this slide with further information in the coming weeks

- Feasibility test concept
  - Get the RTK receivers configured properly (in RTK mode)
  - Set up a basic ground based experiment to test the accuracy of the RTK module (open space)
  - Line up on of the receivers with a ruler and acquire a “0” position
  - Move the receiver alone the ruler to different positions and record data stopping at regular intervals to check later
  - Reset the receiver and begin a new data set
  - Do a high speed test with the RTK by moving the receiver along the ruler quickly (just faster than walking pace)
  - Reset and place the receiver in a car
  - Do a driving test in a parking lot

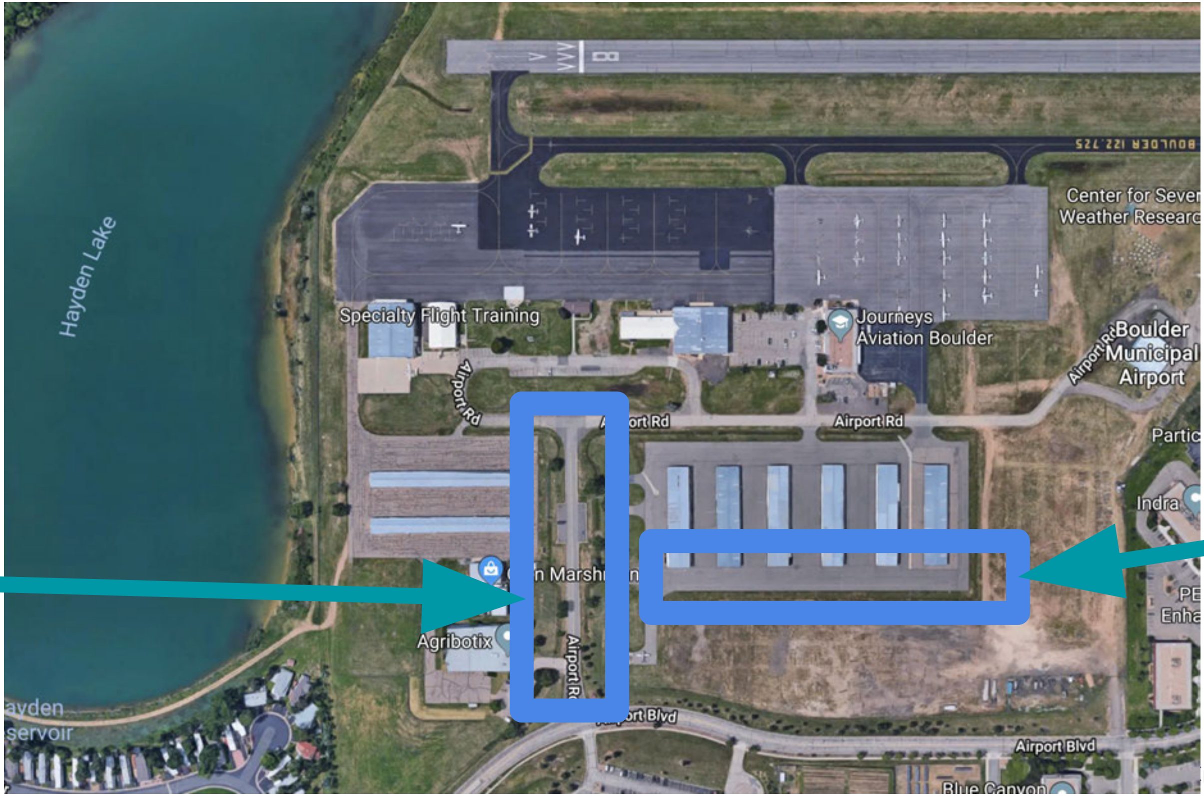
GPS RTK System (2)

- Two receivers
  - One is stationary at a known location near the test site
    - This one is connected to a laptop with the configuration software and does the data collection
  - The other is configured beforehand and mounted to the boom and powered through a 5V USB power interface
    - The flashlight we chose for ideal lighting also provides a USB power output suitable for RTK
- Software interface
  - UBlox software download is free
  - Can configure the receivers beforehand and gathers data from both receivers through the connection of a single receiver (UHF receiver to receiver antennas)
  - Data exported as a GPS file
- Accuracy
  - 2cm

GPS RTK In progress test



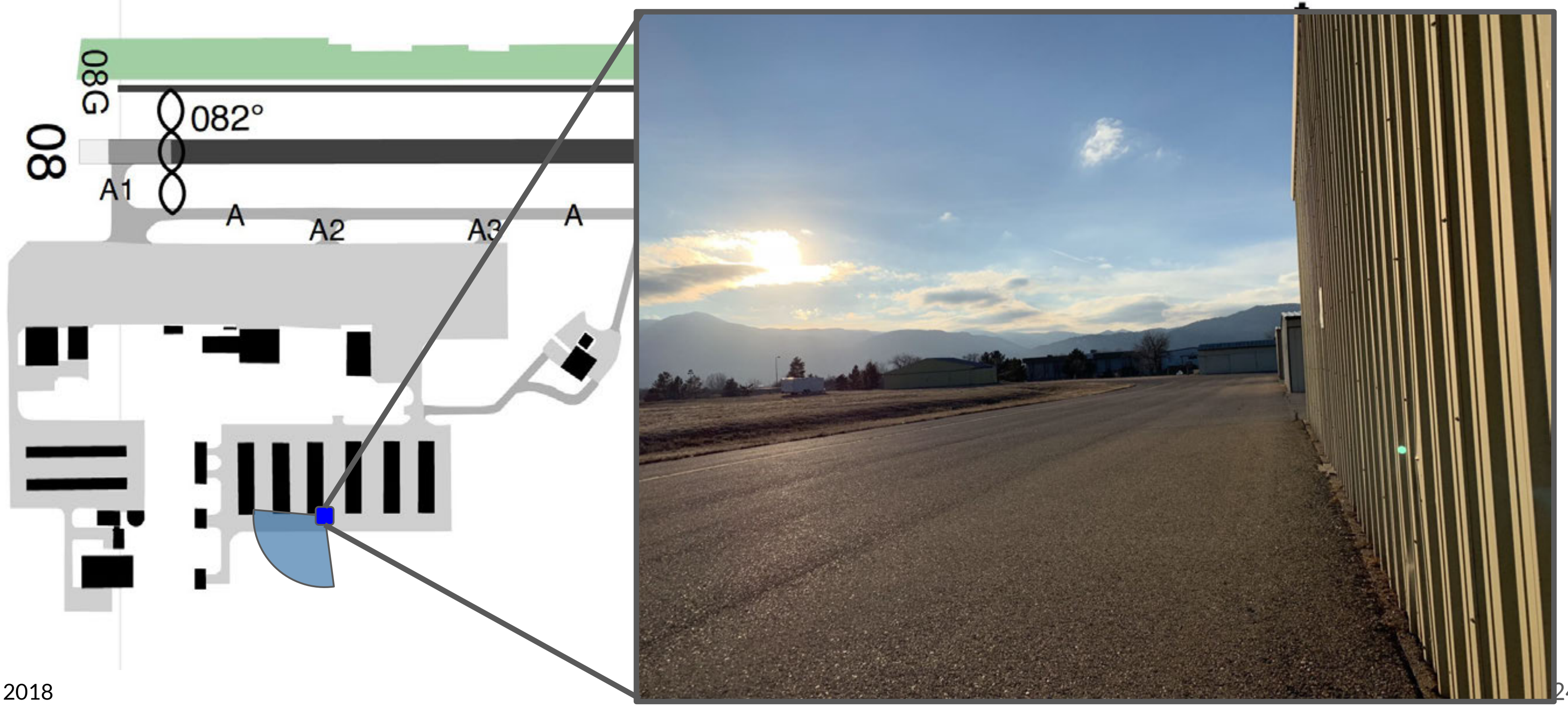
Boulder Airport



Location 1

Location 2

Boulder Airport Test Location

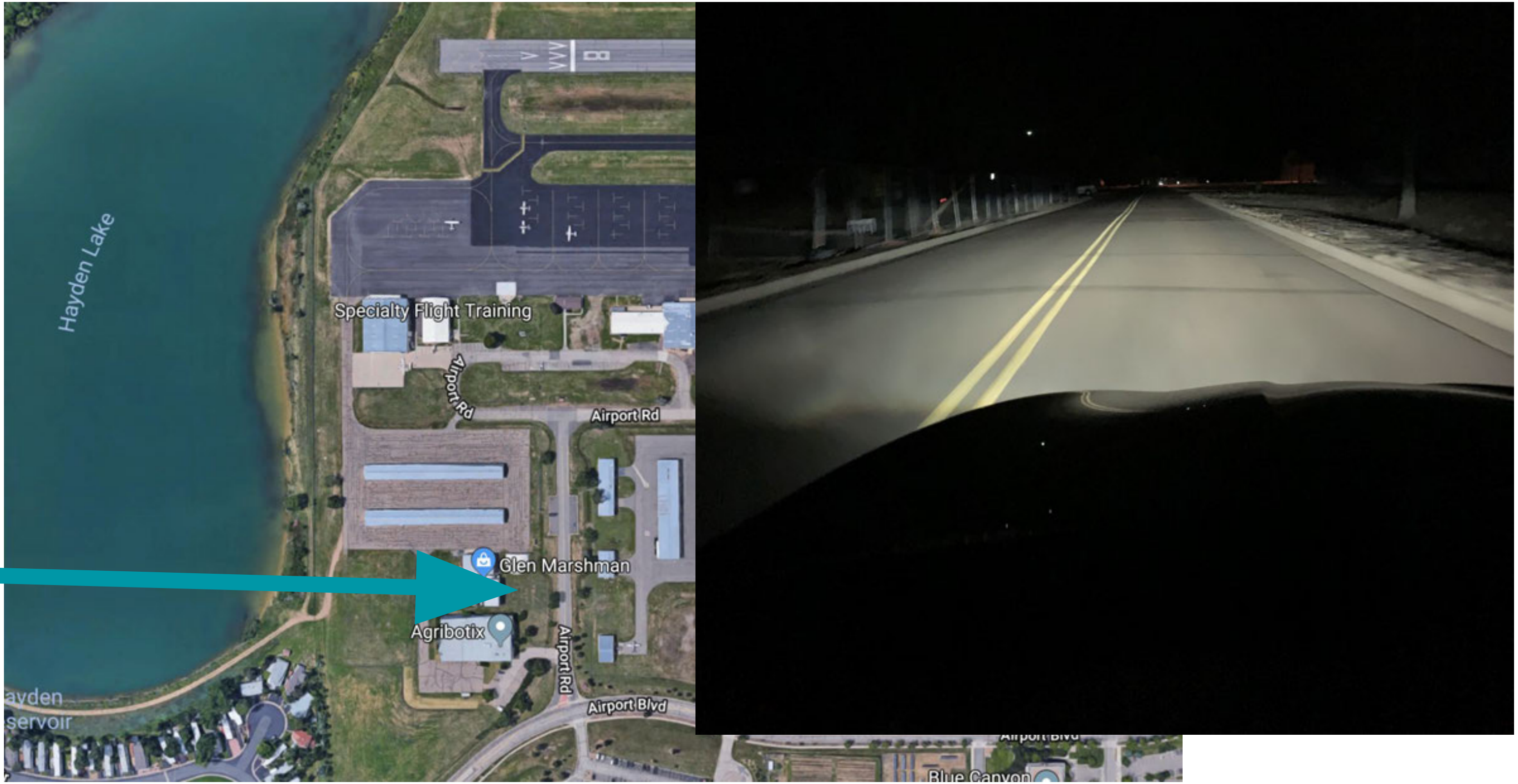


Lighting condition in Boulder Airport

Backup location

After 8 O’clock
0 car per hr

Location 2



100m Test System

- Power required at test site
  - 220V AC for VANTAGE power supply
    - Gasoline powered generator
  - Ideal lighting
    - Battery powered flashlight charged beforehand
    - Only expected to be on during VANTAGE data acquisition
  - GPS RTK
    - Receiver 1 (stationary) powered by connected charged laptop
    - Receiver 2 (Test Boom) powered by flashlight battery or direct USB connection to car USB port
- Additional considerations
  - Flashlight to illuminate
  - Set up of electronics within the test vehicle
  - Electronics required to power RTK and VANTAGE during test
  - Feasibility or Costs of said electronics
  - Make and model of a nice measurement wheel (encoder thing)

100 m Test Procedure

1. Get everything set up and aligned
2. Initialize truth data collection system
    a. Starting the GPS RTK and begin data collection of truth data
3. Start up the VANTAGE flat sat system
4. Send the test case deployment predictions file to VANTAGE
5. Initiate motion of vehicle to bring up to deployment velocity (<2m/s)
6. Capture data
7. End data capture
8. Run software algorithm and process to see if test results were acceptable
9. Reset for new test or take down

100 m Stop Motion Test Setup

- Nearly identical to the 100m test setup and procedure EXCEPT
  - There is no live motion
    - All data points have been predetermined by a chosen test scenario
    - These data points will be generated via simulation and then replicated in the 100m test setup
      - Based on the sampling rates of the sensor system and the rate commanded by the software package this results in roughly 50-100 different capture frames
      - Each capture frame is based on a distance from the VANTAGE system which can be tightly and precisely controlled to within cm of precision both by GPS RTK and by a simple encoder measurement
  - There is an additional way to gather truth data
    - The nice measurement wheel encoder device
- Still meets requirements and can be done more easily than trying to get motion and timing to all work out
  - There is easier control of the system in this case since the test doesn't happen in real time

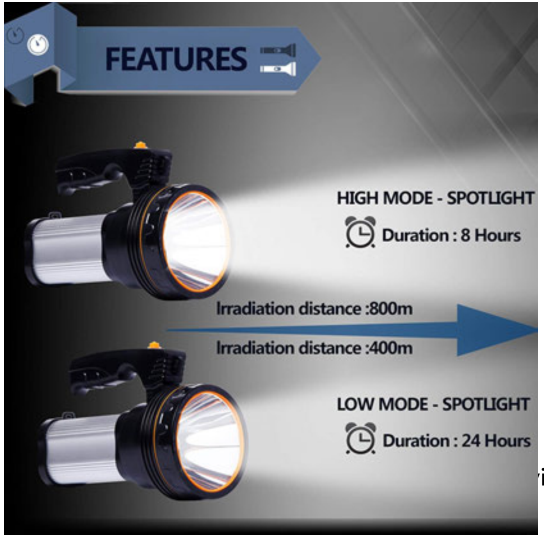
Simulating Ideal Lighting

Necessary Specifications:

- The more light we can get on the target, the better

Flashlight Picked:

- 6000 LUMENS
- LED Bulb
- 9000mAh Rechargeable Battery
- $30



Modular Test Backup

Modular Test BOM

Material	Cost [$]	Quantity	Total Cost	Link
Sheathing Plywood	20.15	1	20.15	https://www.homedepot.com/p/Sheathing-Plywood-Comm
Underlayment (plywood)	15.98	1	15.98	https://www.homedepot.com/p/Underlayment-Common-7-32
Black Spray Paint	3.98	2	7.96	https://www.lowes.com/pd/Krylon-Colormaxx-General-Purp
Pole Sockets	2.48	16	39.68	https://www.homedepot.com/p/Everbilt-1-3-8-in-White-Me
Pole	10.49	3	31.47	https://www.homedepot.com/p/Waddell-1-3-8-in-x-72-in-H
Ball Bearing Wheel	3.16	4	12.64	https://www.globalindustrial.com/p/material-handling/conve
PVC Pipe	17.41	8	139.28	https://www.homedepot.com/p/JM-eagle-3-in-x-10-ft-PVC-
PVC Pipe Corner Piece	2.66	4	10.64	https://www.homedepot.com/p/3-in-PVC-DWV-90-Degree-
PVC Pipe Connector	5.99	6	35.94	https://www.acehardware.com/departments/plumbing/pipe-
Rope	8.71	1	8.71	https://www.homedepot.com/p/Everbilt-1-4-in-x-50-ft-Whit
Screws	7.98	1	7.98	https://www.homedepot.com/p/Grip-Rite-1-1-4-in-Construc
Light Source	29.69	1	29.69	https://www.amazon.com/dp/B074P5N3RG/ref=psdc_2445
Total			360.12	

RECUV Test Location

Vicon Specifications:

- System of IR cameras
- Position Error of 0.0775 mm
- 100 Hz data capture
- Latency of 16.87 ms

Modular Test Plan/Procedure

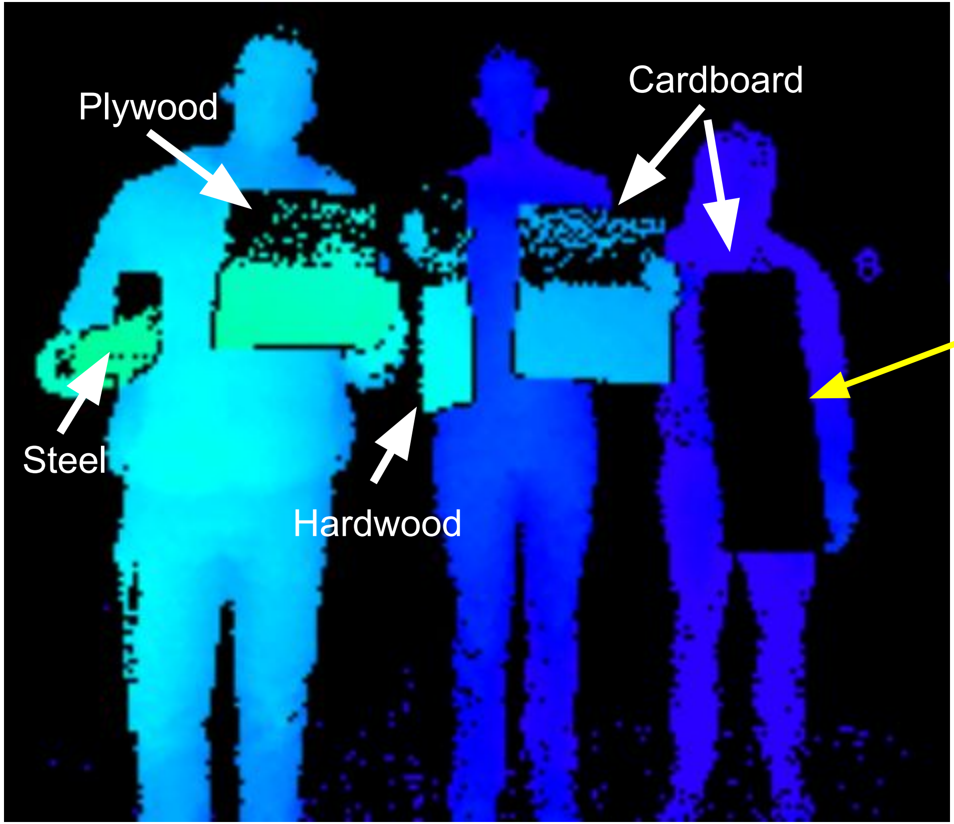
Nominal Deployments → Off-Nominal Velocity Deployment → Off-Nominal Deployment Time → Failed Deployment

1. RTK GPS placed inside first Mock CubeSat and powered on
2. Internal lighting turned off and ideal light source turned on
3. VANTAGE powered on **(FR.2, FR.3)**
4. Motor commanded to accelerate cart
5. Cart enters VANTAGE FOV and data collection begins **(FR.1, FR.5)**
6. Motor commanded off
7. Data collection ends
8. Data processing begins **(FR.6, FR.7)**
9. Data offloaded **(FR.8)**

IR Absorbing Background

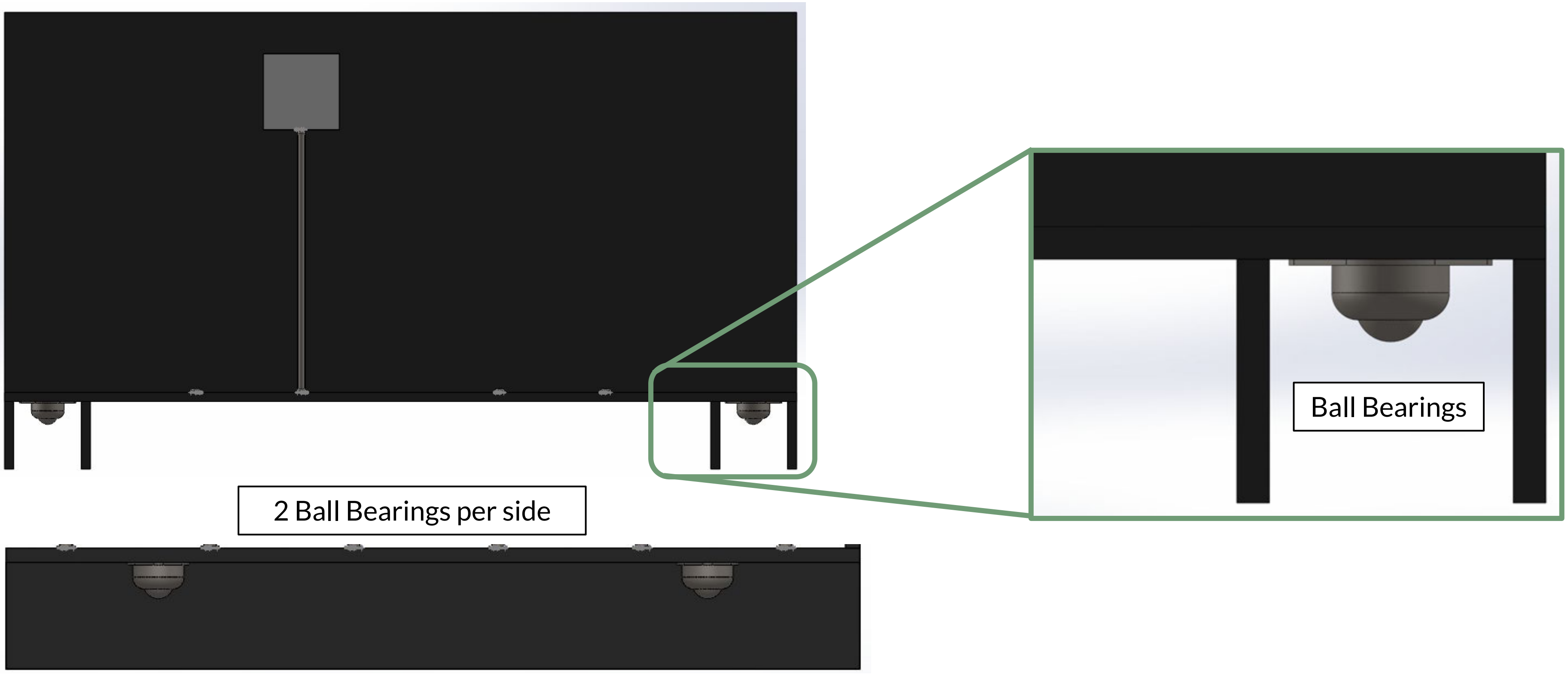
Paint on top

No paint on bottom



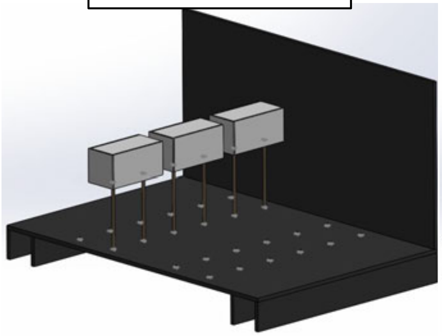
Paint

Modular Test Rail to Sled Interface

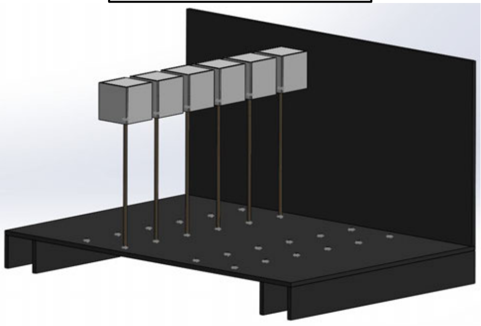


Mock CubeSat Cart

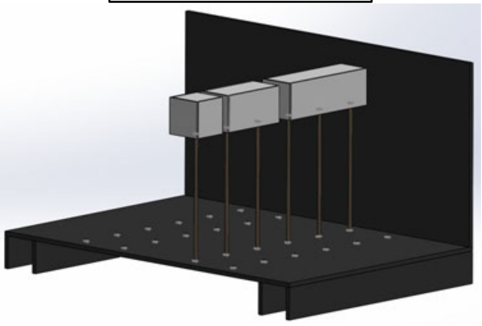
3 2U from Tube 4



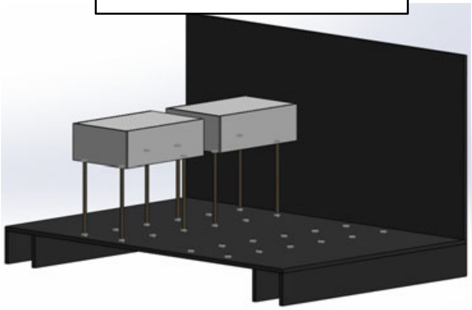
6 1U from Tube 2



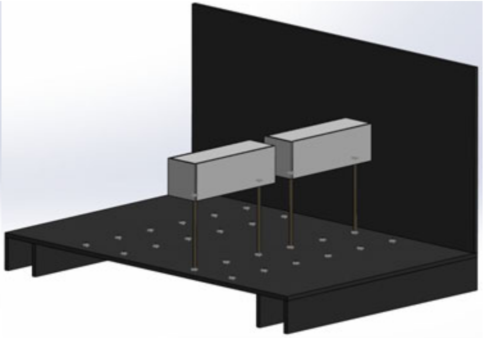
Mix from Tube 6



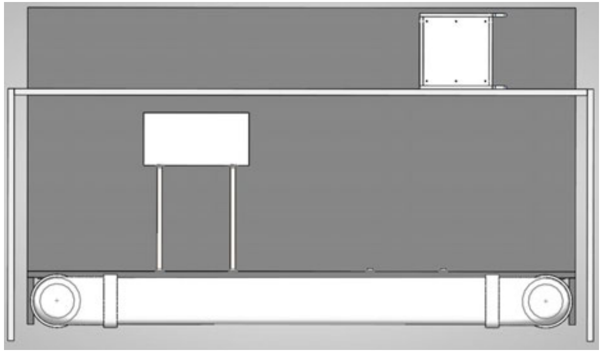
2 2x3U from Tube 4/3

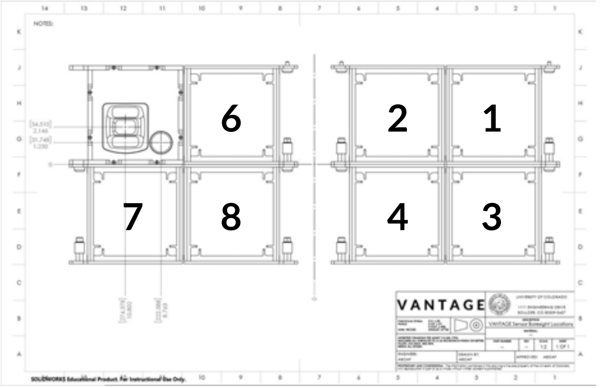


2 3U from Tube 8

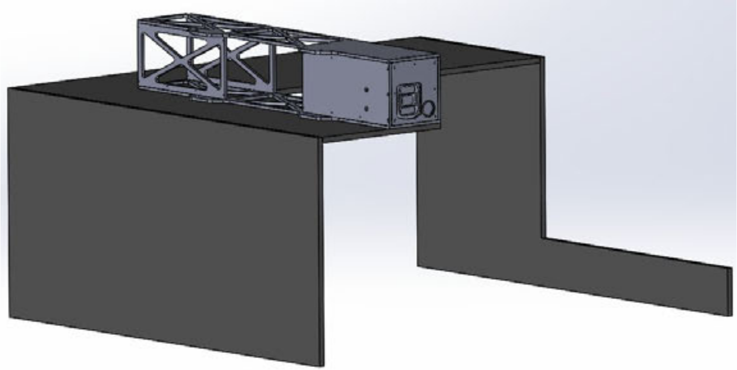


VANTAGE Shelf





- Shelf holds VANTAGE package at the height and position of the deployer tube it would replace
- Design allows for mock deployments from tubes in line with VANTAGE



Cart Bottom Board Deflection

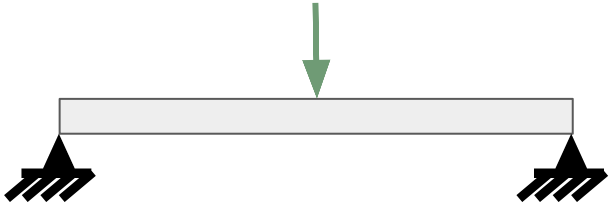
Assuming Simply Supported Beam:

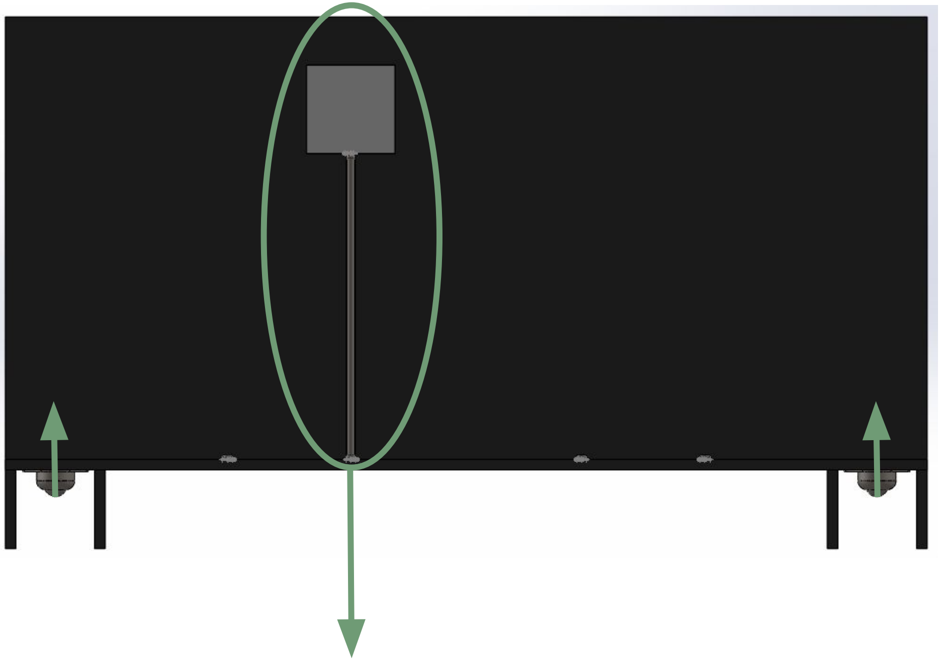
- Mass of 6 1U CubeSat Assembly: 0.96 kg
- F = 9.414 N
- L = 1.041 m
- E = 11 GPa
- I = 0.502 kg-m^2

Max deflection δ = 4e-11 m

$$\delta_{max} = \frac{FL^3}{48EI}$$

FBD:





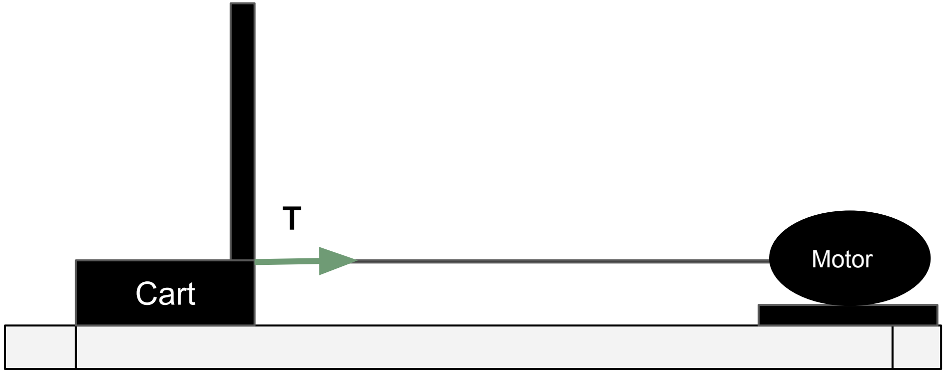
Effects of Max Motor Pulling Force

- During cart acceleration, max force produced: **T = 63.45 N**
- Interface between cable and cart is a bike hook.
- Bike hook has 25 lbf weight limit = **111.206 N**
- **FOS = 1.75**

Bike Hook

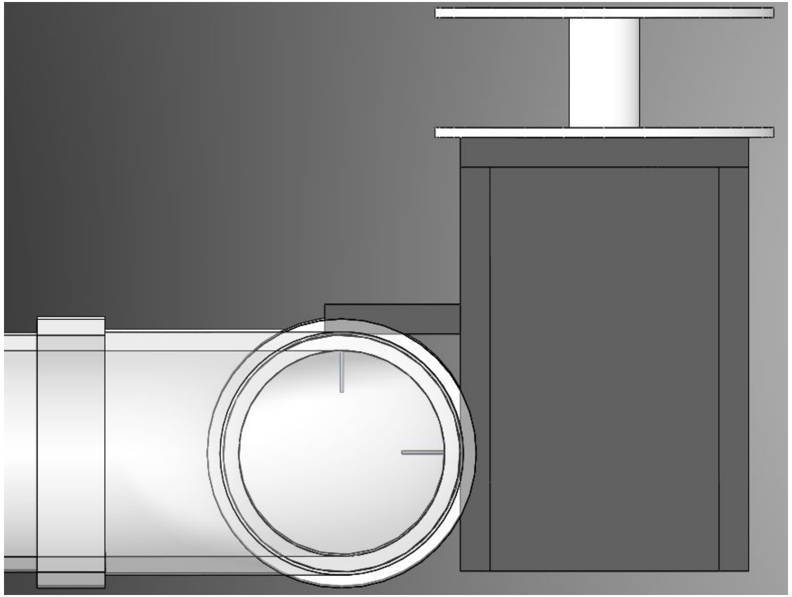
Image Credit: HomeDepot

FBD:



Motor Mount to Rail

- During cart acceleration, max force produced: **T = 63.45 N**
- Interface between motor and rail is 4 1-¼” steel screws



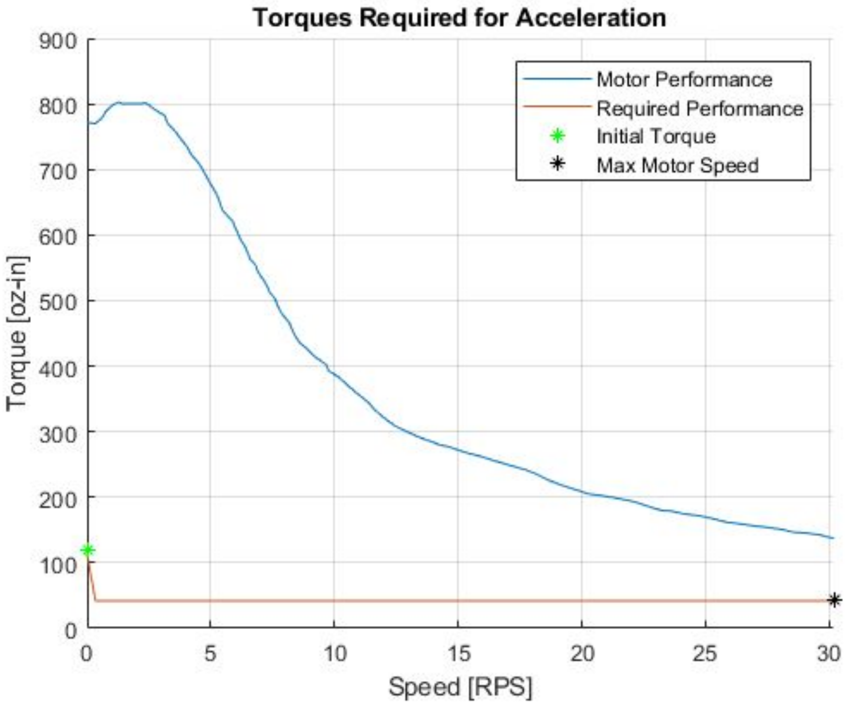
Motor Feasibility (1)

Initially must overcome static friction to get ball bearing wheels to roll:

- Requires **T = 119 [oz-in]**
- Well under torque motor produces
- **FOS = 6.5**

After wheels begin to roll:

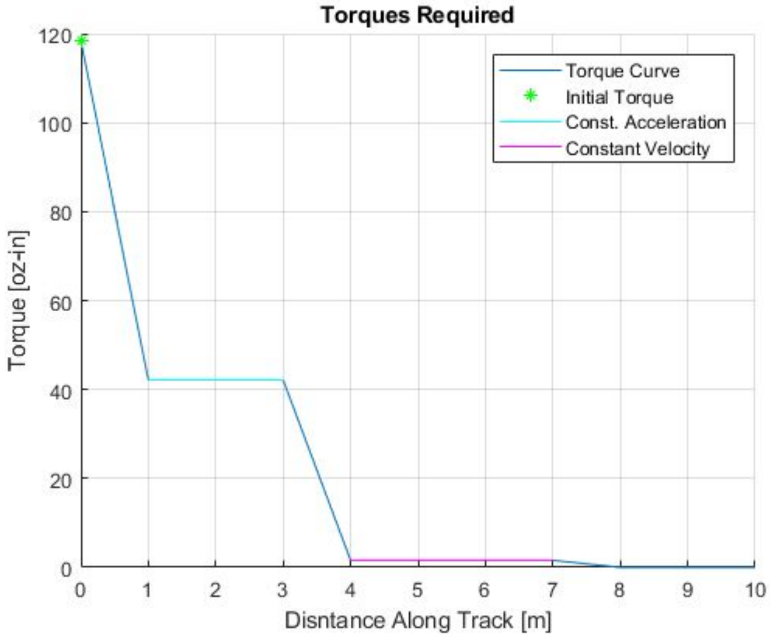
- Requires **T = 43 [oz-in]**
- Required up until max motor speed: **30 [RPS]**
- At 30 [RPS], **FOS = 3.25**



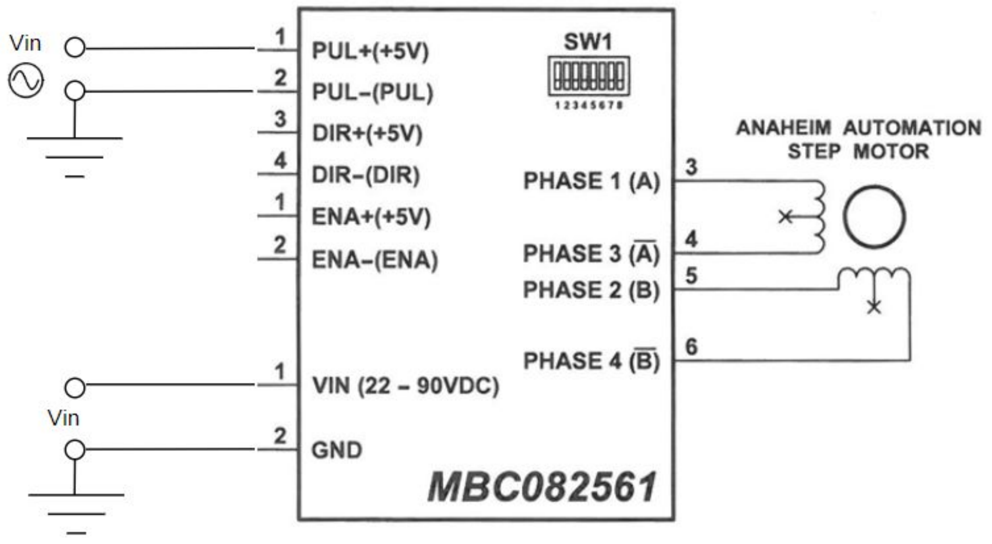
Motor Feasibility (2)

Don’t currently have control designed for motor in LabView

- Required torques already known
- Motor is capable of producing these torques



Motor Wiring Diagram



Sensors Backup

Camera-Only Accuracy Feasibility

Image from field test

Measurement and Uncertainty Determination Process

Known Geometry → Depth Measurement

Field Test Images → Manual Feature Extraction → Depth Measurement → **Range / Cross-Range Error from Edge Uncertainty**

Inputs ⟵ ⟶ High-Level Algorithm (Detail in Backup)

Actual Range	Measured Range	Range Uncertainty (1σ)	Cross-Range Uncertainty	Error + Uncertainty
5.0m	5.12m	0.30m	0.22 cm	42 cm > 10cm
100.0m	94.33m	4.76m	0.24 m	10.43 m >10 m

A camera alone does not satisfy position measurement requirements

Req.	Summary
DR 6.1	Position Accuracy (10 cm for 3-10m ,10% of range to 100 m)

TOF Camera: Error Analysis

TOF Sensor Error Figures
(from Data Sheet)

Range	Depth Error
>3m	7 mm
3-5 m	10 mm
5-7 m	15 mm
7-8 m	20 mm

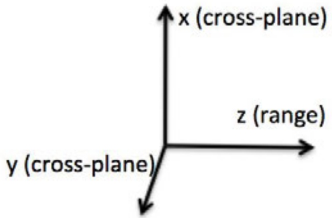
$$v = \frac{\Delta x}{\Delta t}$$

$$\delta v = \sqrt{\delta x^2 + \delta t^2}$$

Electronic timing of measurements assumed to be very accurate. $\Rightarrow$ $\delta t << \delta x$

Assuming constant velocity, the velocity estimate is refined by each position measurement.

$$\delta v_{refined} \propto \frac{\delta v}{\sqrt{N}}$$

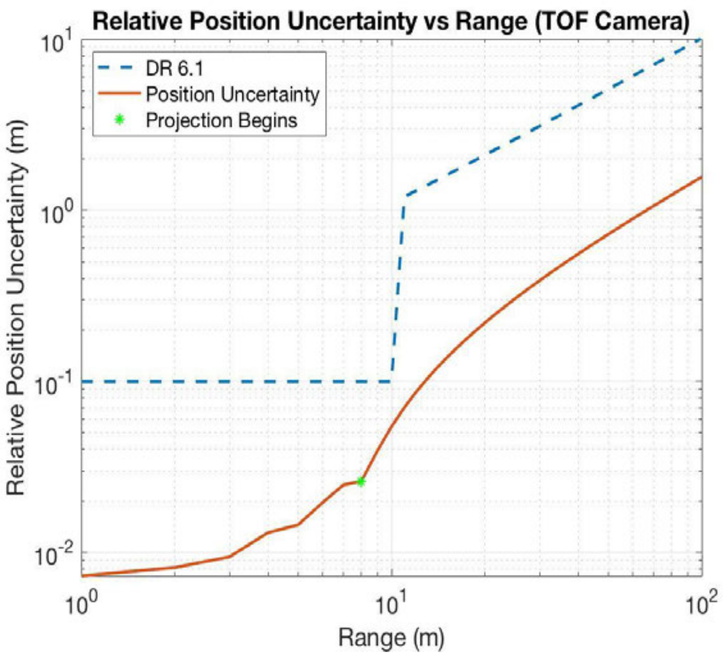


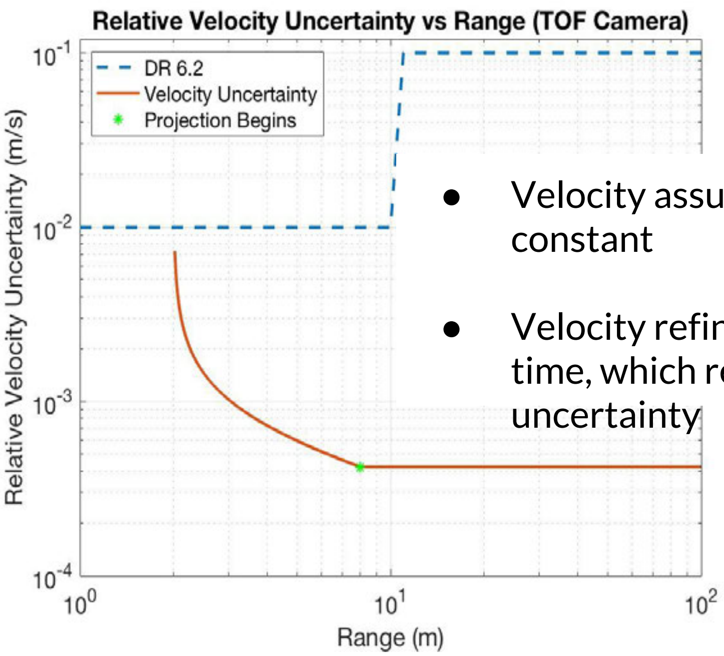
Cross-plane accuracy approach: Assumed sensor can measure geometric center to ½ pixel.

N = Number of TOF Position Measurements - 1

Assumed conservative TOF measurement rate of 12 fps (max TOF FPS = 25 FPS)

Sensor Requirements Satisfaction





- Velocity assumed constant
- Velocity refined over time, which reduces uncertainty

Req.	Summary
DR 6.1	Position Accuracy (10 cm for 3-10 10m ,10% of range to 100 m)
DR 6.2	Velocity Accuracy (1 cm/s to 10 m , 10cm/s to 100m)

Other DR's

1.1: The system shall use a camera to capture images of mock CubeSats.
SATISFIED-Verify By Inspection

1.2: Imaging subsystem shall have a FOV greater than 20° horizontally
SATISFIED:
Sensor Size: 7.41 mm x 4.98 mm
Lens Focal Length: 16 mm
Horizontal FOV~26 degrees

Using triangle geometry: $(FOV/2) = tan^{-1}(\frac{Sensor Size/2}{Focal Length})$

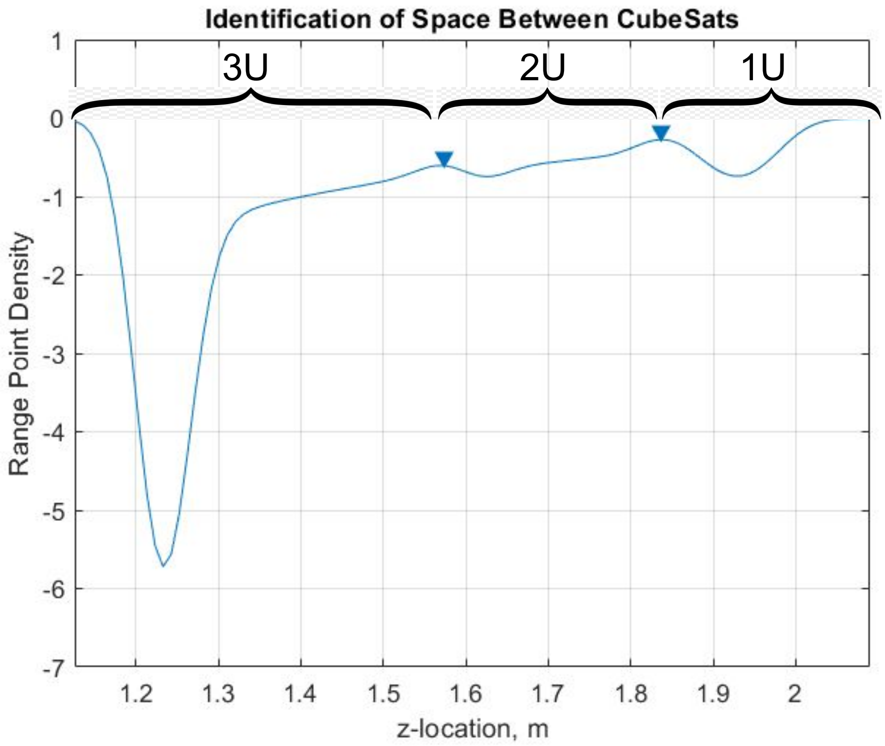
1.3: Imaging subsystem shall produce at least 2 images of each mock CubeSat deployed by the test system.
SATISFIED: We expect to take images at a rate of about 1 Hz, we should have plenty of images.

1.4:Imaging subsystem shall produce in-focus images of mock CubeSats within 10 m.
SATISFIED: We will set the focus of the lens to be clear at about 10 meters. Verify by inspection

1.5: Sensor subsystem shall have a sensing FOV of at least 20° horizontally
SATISFIED: Both Sensors have FOV's that exceed this. ToF FOV= 40x30 deg.

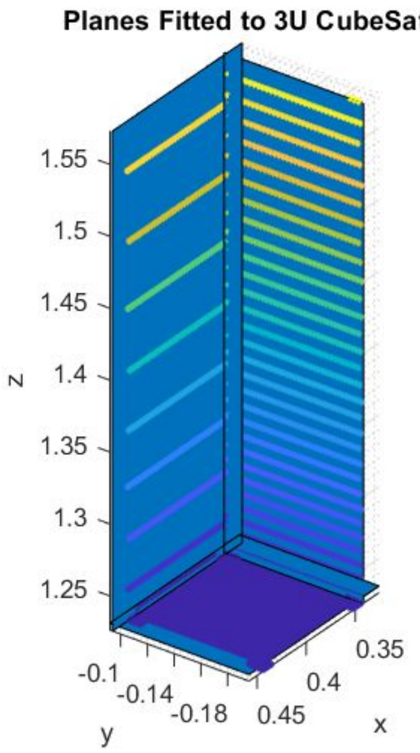
Software Backup

TOF CubeSat Identification



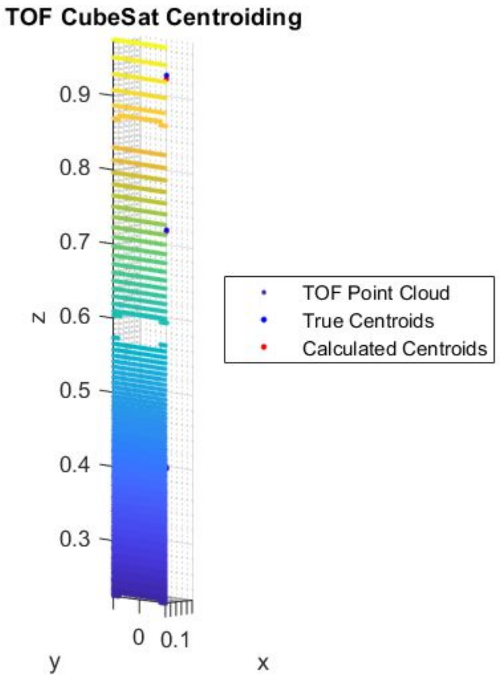
- TOF point cloud splitting method:
  - Convert point cloud into z-direction (aka downrange) point density using K-Squares method
  - Apply findpeaks() to point density to determine regions of minimum point density
  - These points are used to separate the CubeSat

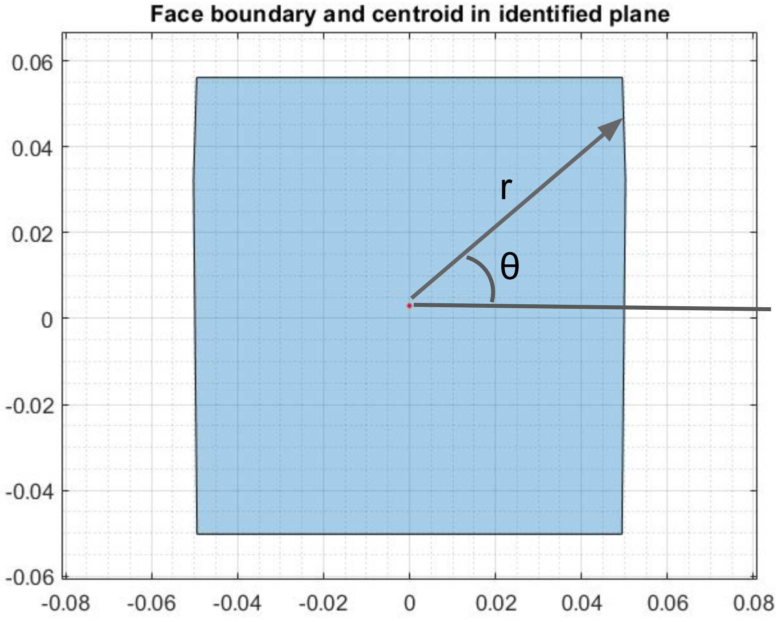
TOF Plane Identification



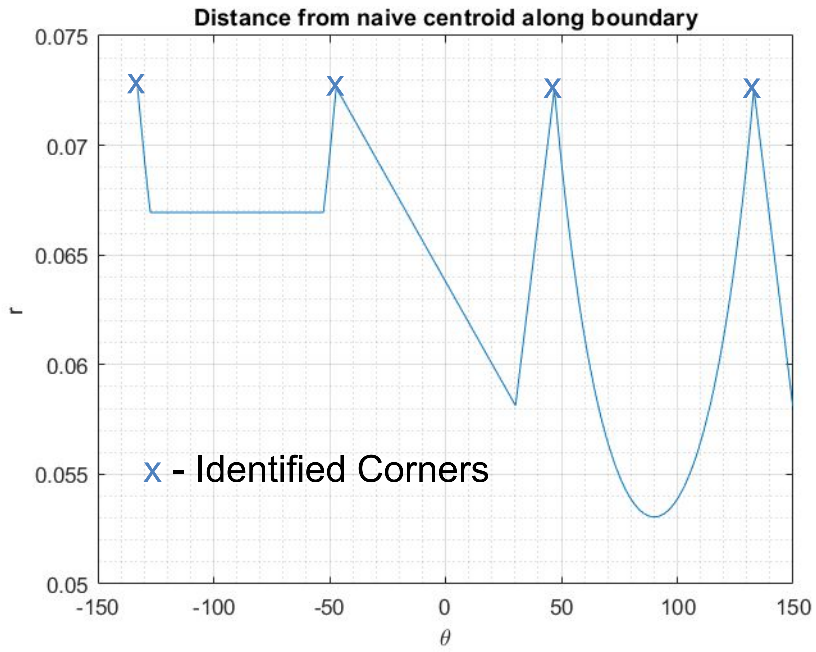
- Simplified plane identification method:
    - Use MATLAB's pcfitplane to find most heavily populated plane with a specified heuristic parameter: the maximum allowable distance of a point from the plane
    - Remove points associated with the previous plane and use pcfitplane to find most heavily populated plane in remaining point cloud
    - Repeat until pcfitplane cannot find a plane or three planes have been found

TOF One-Plane Centroiding



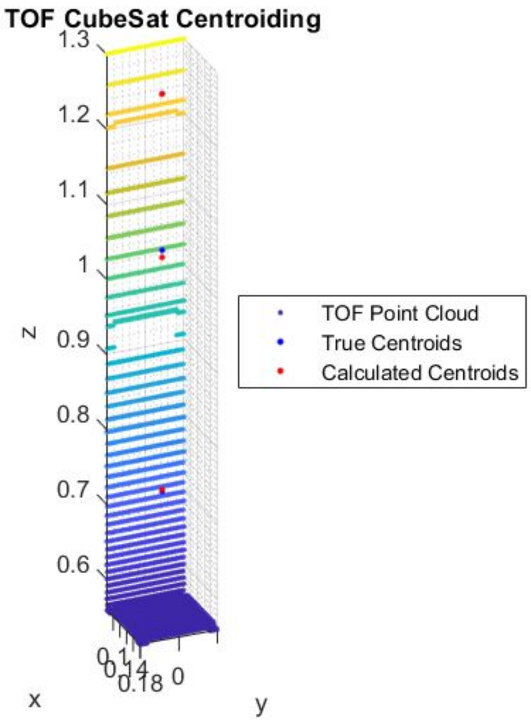


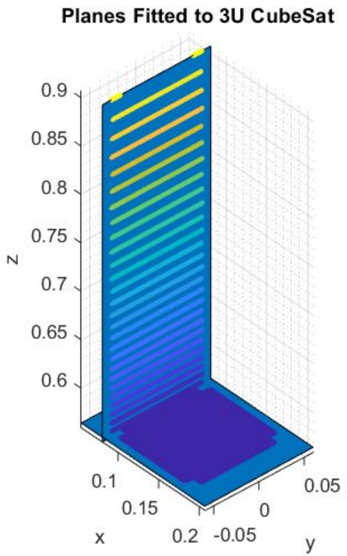
TOF One-Plane Centroiding



- Simplified corner identification method:
  - Up to four large peaks in a graph of distance from naive face centroid to boundary describe the locations of corners in the face
  - Based on the number of corners and their location relative to the naive centroid of the CubeSat face, the true centroid of the CubeSat face can be determined
  - Note: CubeSat U is defined by the deployment manifest and assumed to be known

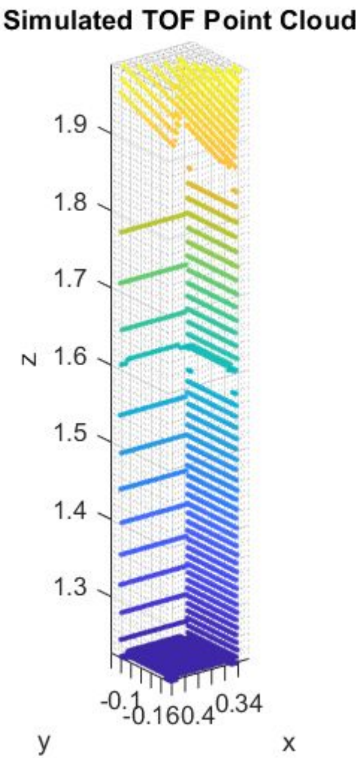
TOF Two-Plane Centroiding

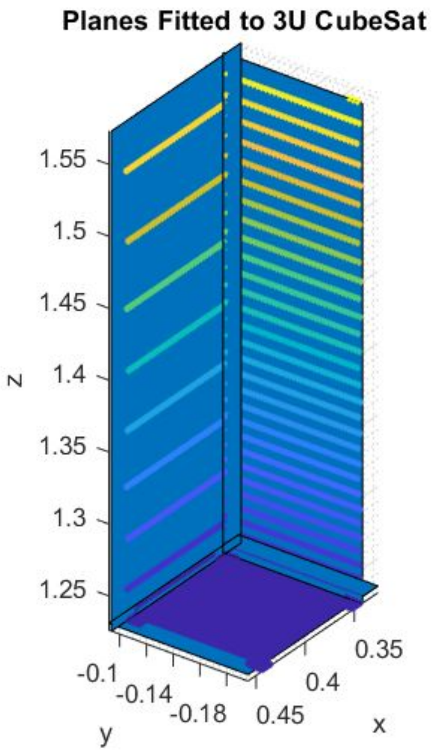




- Solve for line of intersection of the two planes
- Project point cloud onto the line of intersection
- Determine midpoint of projected pointspread
- Project from intersection midpoint into CubeSat to calculate centroid

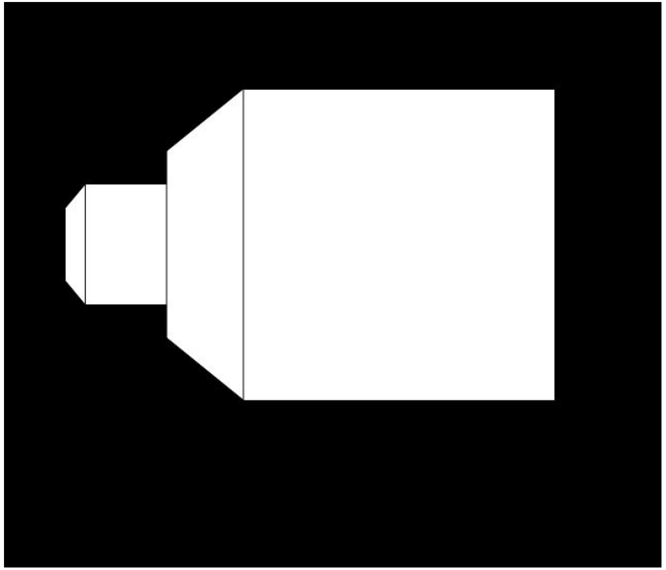
TOF Three-Plane Centroiding

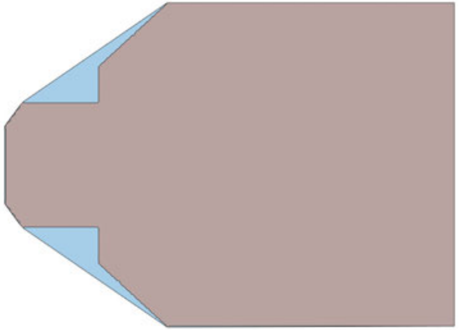




- Solve for intersection point of the three planes
- Project from intersection point into CubeSat to calculate centroid

Partial Occlusion





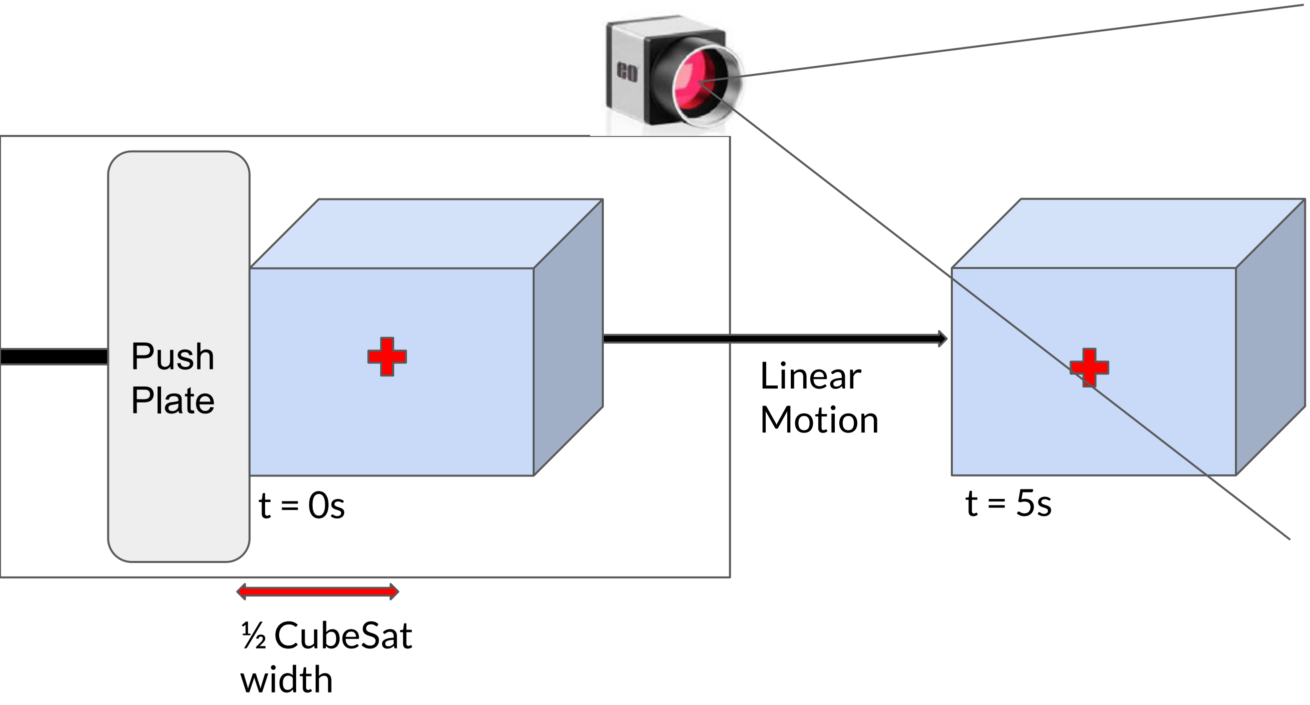
Using the computational geometry library in Matlab, we can use the extracted image border to create a convex hull, and compare it with the boundary itself.

If the difference between the two is not negligible, the differences between the two can be used to remove the partially occluded cubesat hull.

Deployment Prediction Validation

- Necessary to validate the following:
  - CubeSats launch within 3 seconds of expected time given in deployment manifest
  - CubeSat velocities are within the range of 0.5-2m/s
- Launch time validation can be done by linearly interpolating from first image with detected CubeSat centroid backwards to the centroid position of ½ CubeSat width, where the back face is resting against the pusher plate
- Launch velocity validation will be trivially completed with existing linear velocity result
  - Motion of CubeSats will be linear, so output velocity will be equivalent to launch velocity, which can be directly compared to the manifest

Off-nominal Launch Time



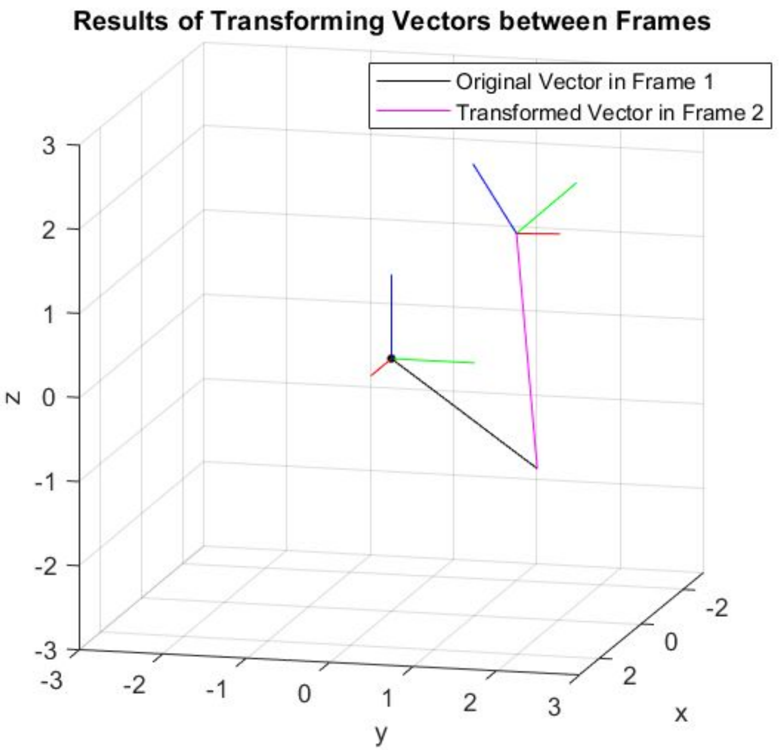
- Linear velocity be known from post-processing results
- Time at which first image with CubeSat can be used to extrapolate backwards and find CubeSat position at t = 0s
- CubeSat position at 0 +/- 3s should be its origin

TOF Future Work

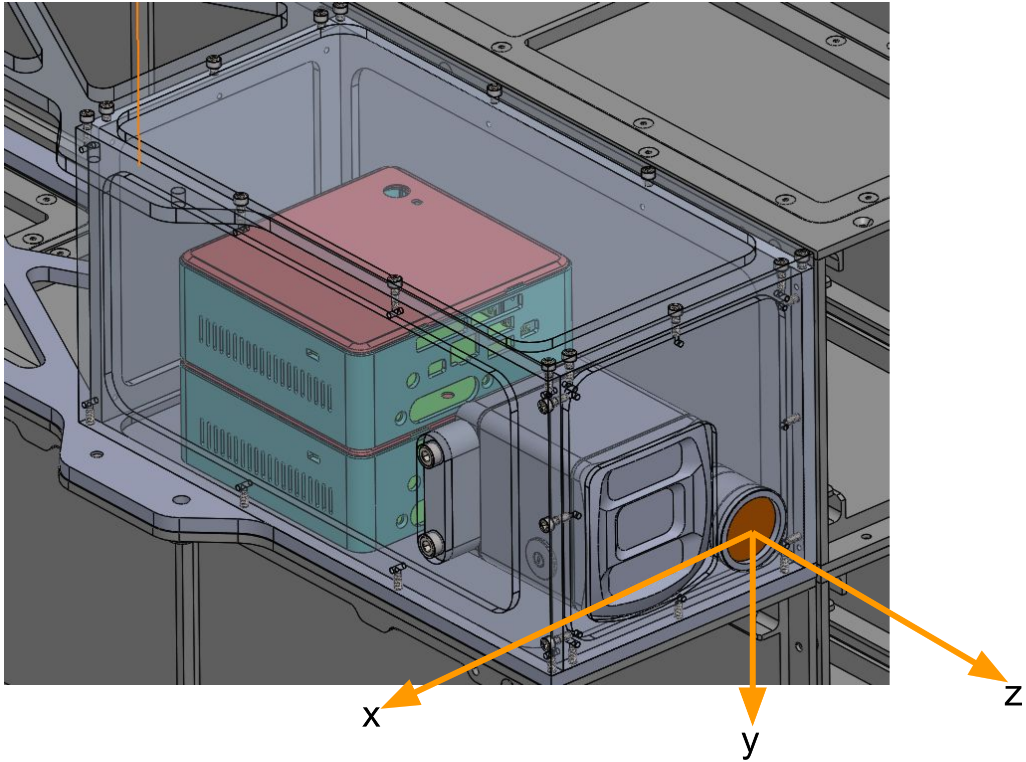
- Make all heuristic parameters adaptive (e.g. pcfitplane's maximum allowable distance of a point from the plane, findpeaks' maximum peak height)
- One-plane method
  - Add ability to handle detection of only two corners
  - Add ability to handle partial-plane centroiding when entering FOV
- Two-plane method
  - Add ability to handle partial-plane centroiding when entering FOV
- Add ability to predict cubesat locations so that TOF data can still be used even when CubeSats cannot be differentiated based on the raw point cloud

Transform Method

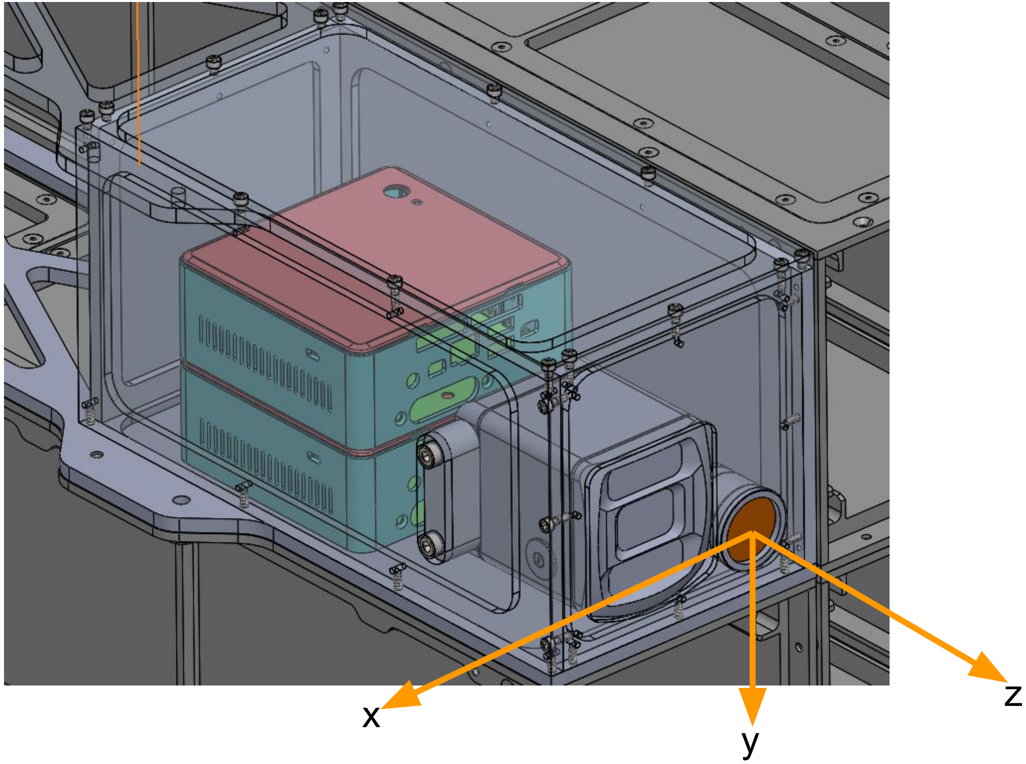
- This method will be used to transform vectors between the Camera Frame, the TOF Camera Frame, and the VANTAGE Frame in which CubeSat state is measured
- The transform method is able to receive data to define the relationship (rotation and offset) between an arbitrary number of frames
- It is then able to transform a vector between any frames whose relationship has been defined



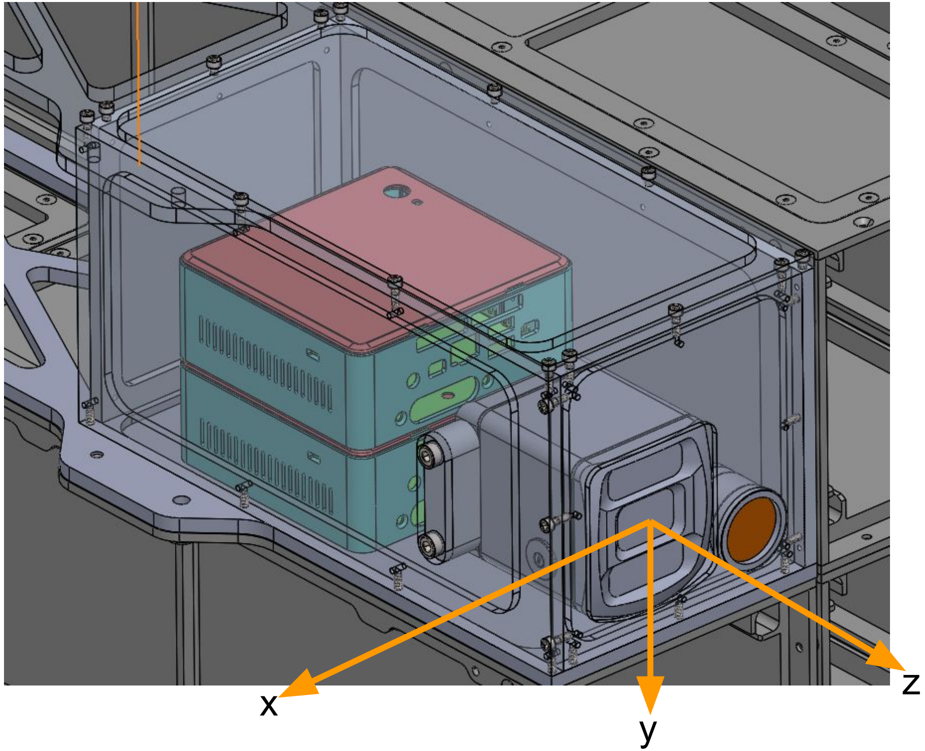
VANTAGE Frame



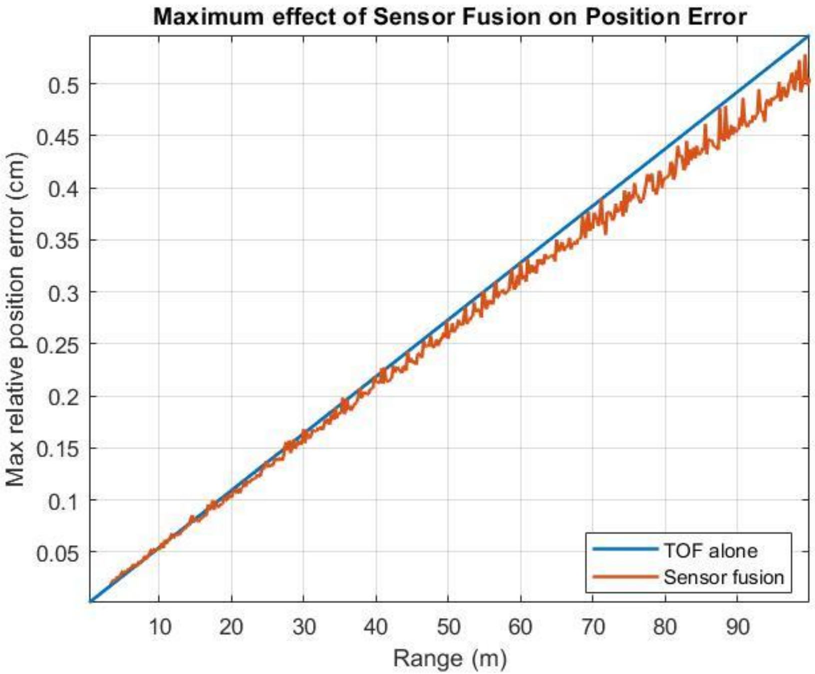
Camera Frame

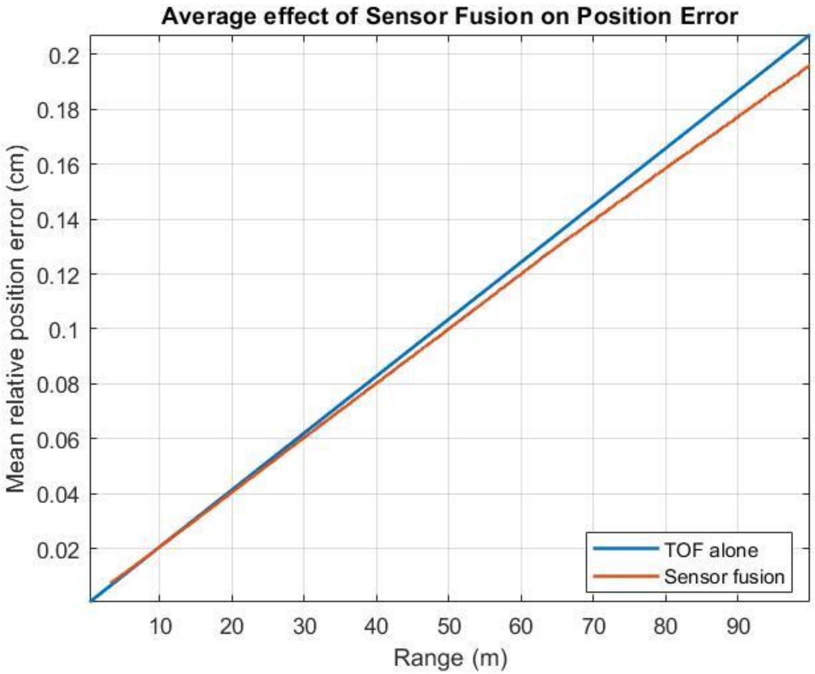


TOF Frame

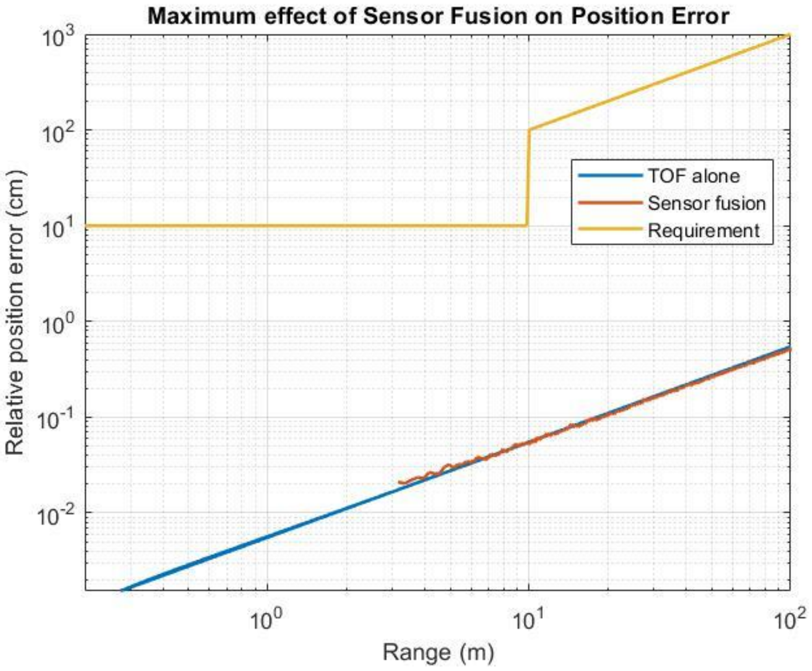


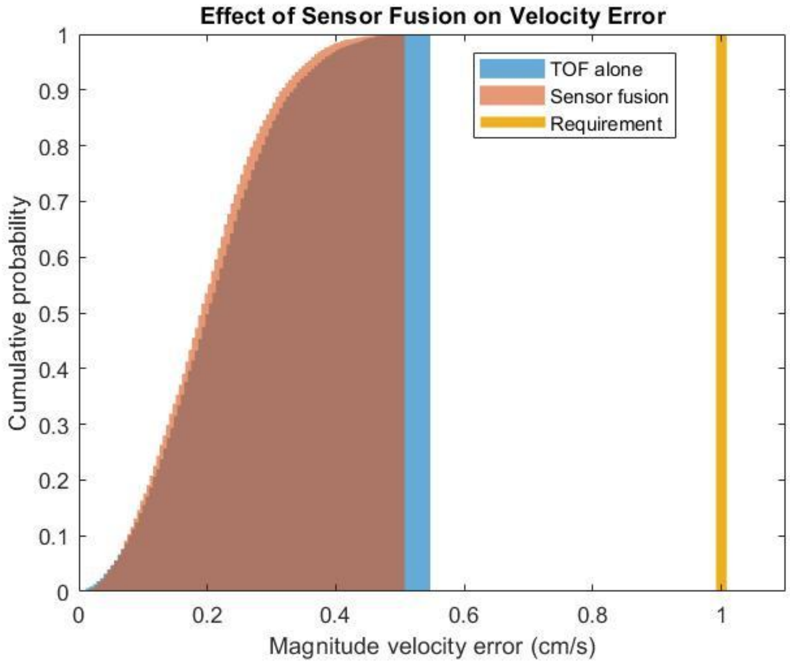
Sensor Fusion Effectiveness Part 1





Sensor Fusion Effectiveness Part 2

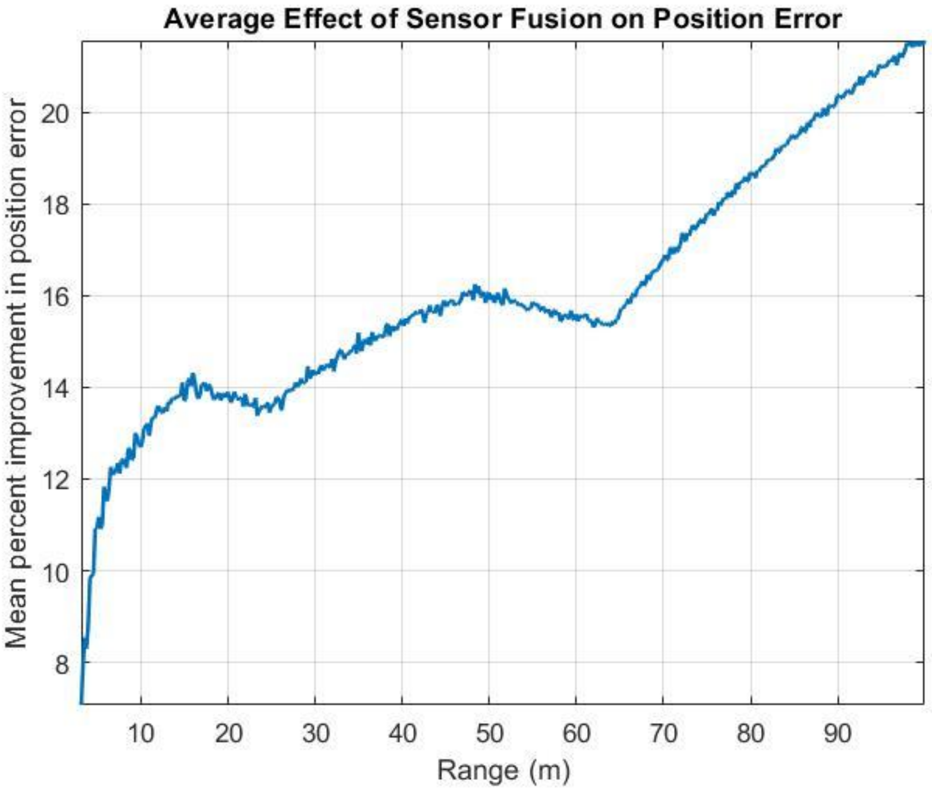




Sensor Fusion Verification

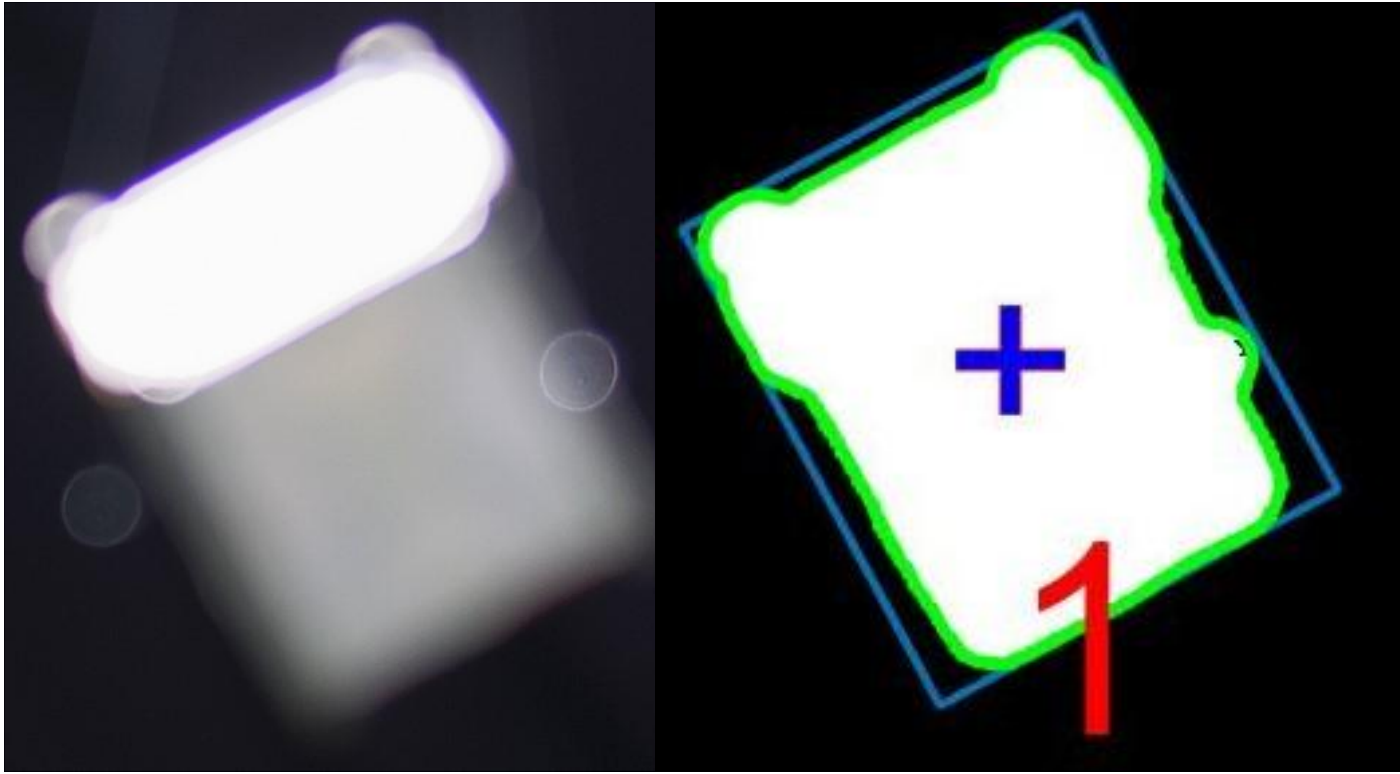
Monte Carlo Simulation:

- Verification of sensor fusion effectiveness
- Maximum error as a function of range
- Gaussian distribution of ToF error for 0.25-3m
  - Propagated to 100m
- Gaussian distribution of camera error for 3-100m



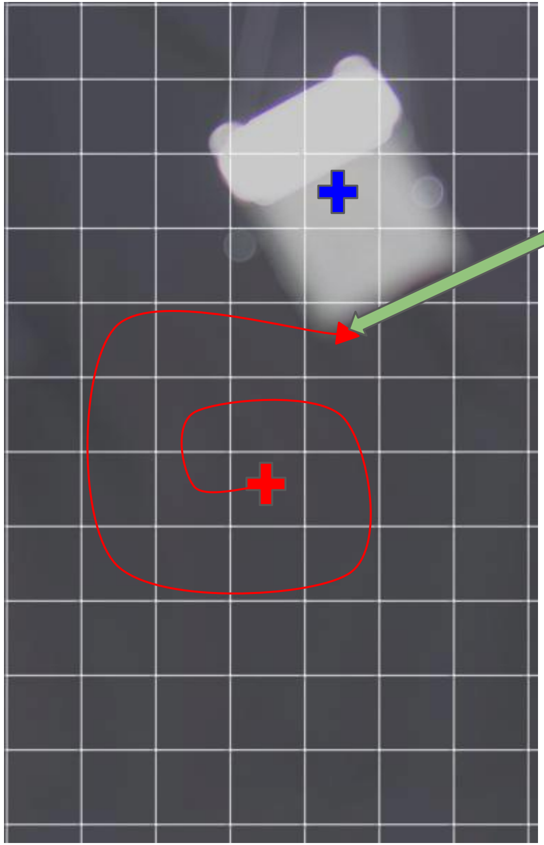
Boundary Boxes

- In some orientations, binarization may eliminate pixels that correlate to CubeSats
- Bounding boxes encapsulate all pixels captured within the box



Prediction Model Search Alg.

- Search starts from centroid predicted based on sensor fusion
- Search spirals outwards, seeking the first pixel occupied by a boolean True value
- Algorithm then searches neighbors, determining boundary of CubeSat
- Updated centroid is determined in significantly less time than searching full image



Boolean True detected

Prediction Model

- To significantly improve the runtime of the post-processing, a prediction model is implemented based on extrapolated TOF data, as well as optical camera data past the first optical image processing
- After detecting a centroid from the weighted-average sensor fusion, the expected next position in the optical camera will be determined based on rectilinear motion assumption
- In the next frame, the prediction model provides an expected pixel (H,V) location for the centroid
- Edge detection begins its search for a binary True value outwards from this location

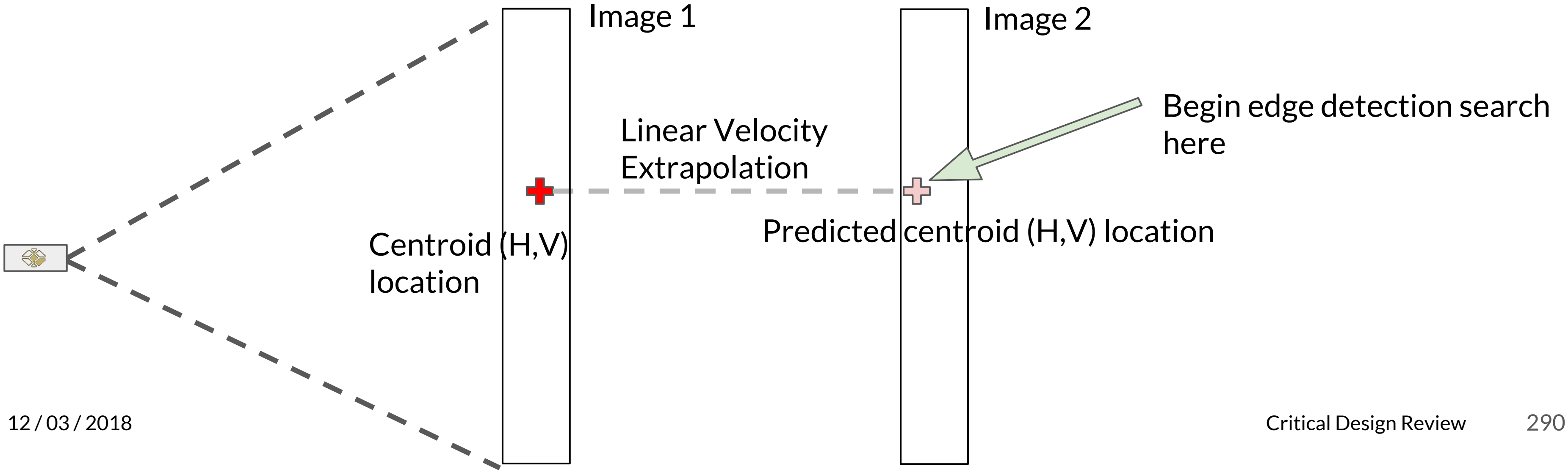
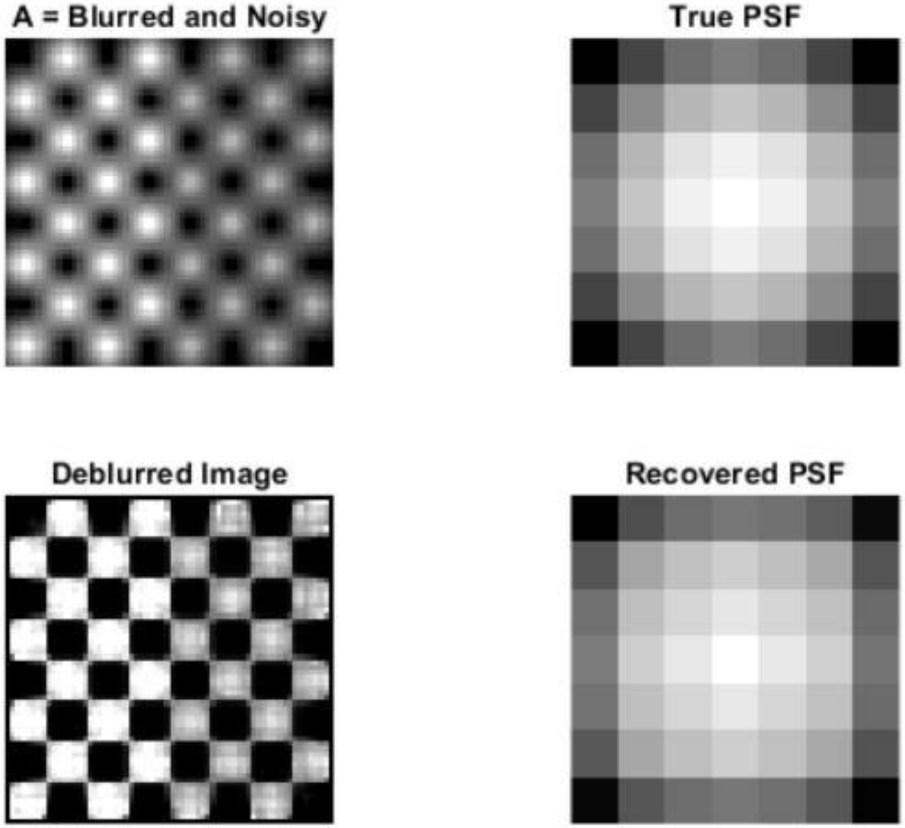


Image Deblurring

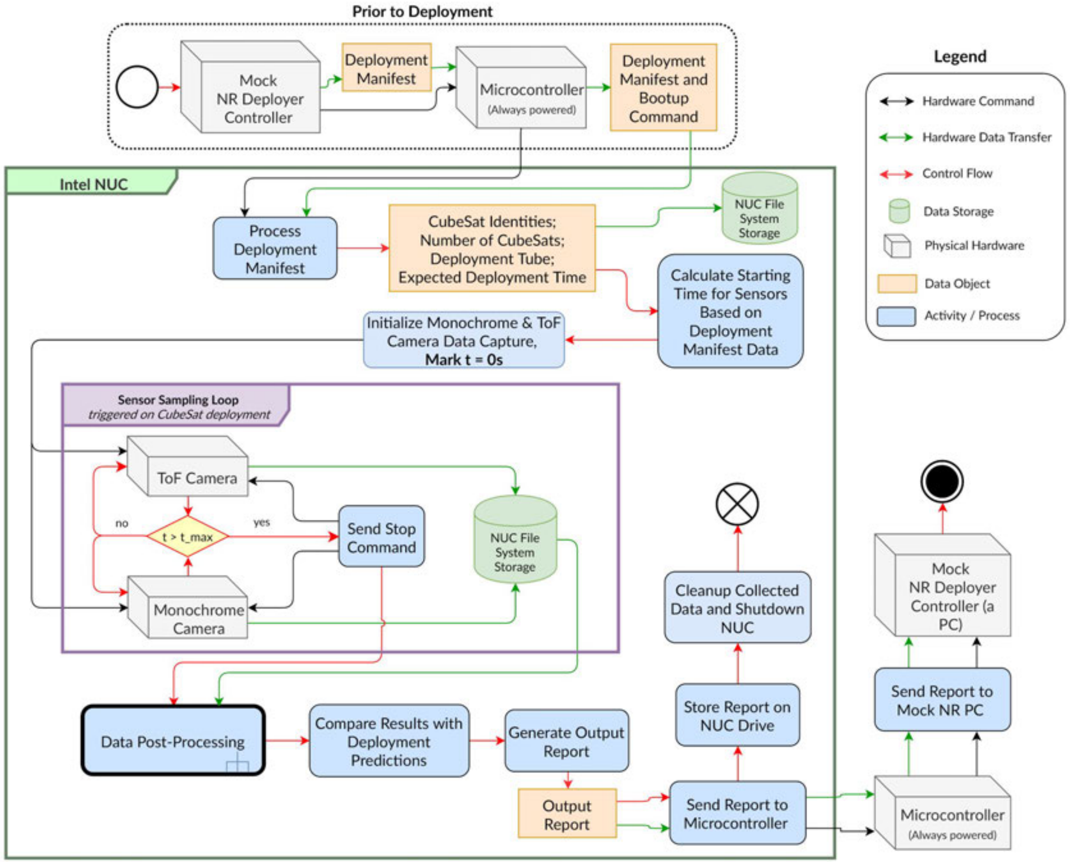


- To deblur an image, an accurate Point-Spread Function must be known
- This level of accuracy to camera blur can only be achieved using field data (using actual VANTAGE camera)
- Resolving a Point-Spread Function requires initially deblurred results of the same image
  - Rigorous testing is necessary
- Point-Spread Function is impossible to achieve until Spring semester when camera is accessible
- When a PSF is determined, image deblurring is more realistic

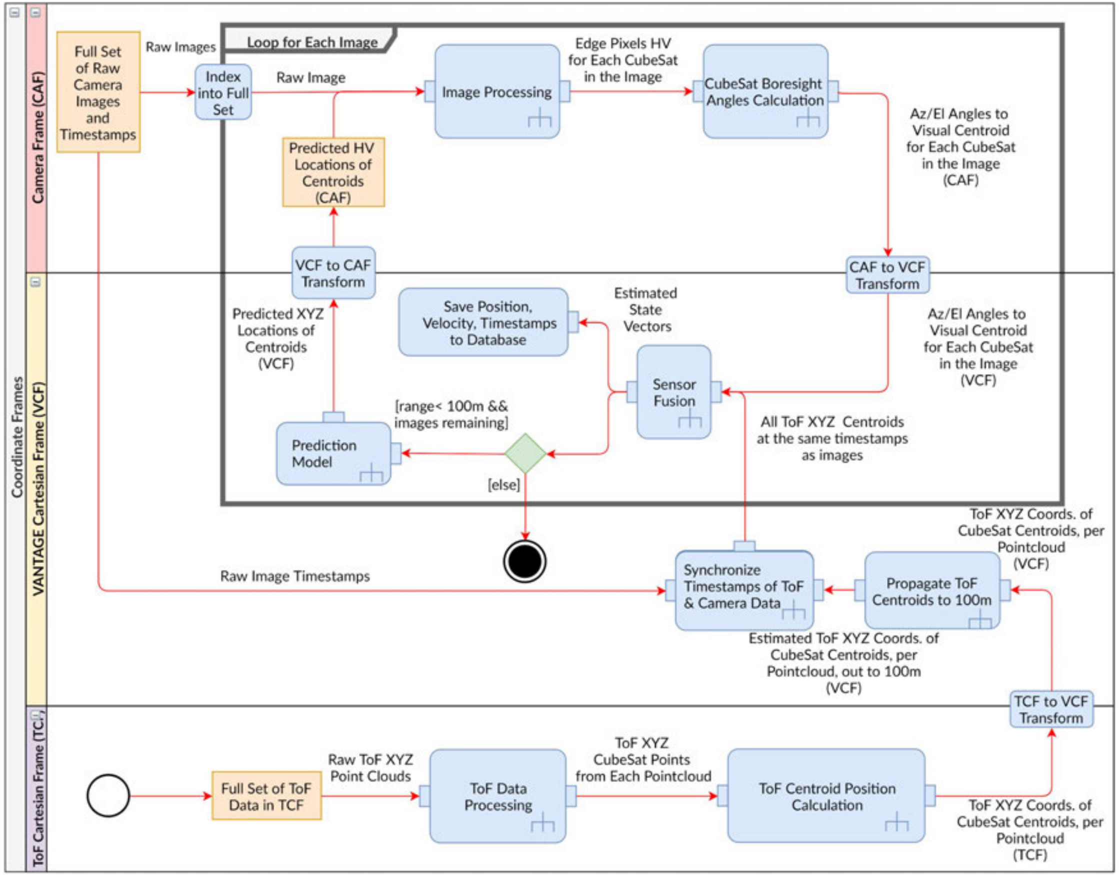
Image Deblurring

- Image deblurring is initially motivated by a desire for more accurate edge detection
- For the case of using boundary boxes to resolve occlusion, image blur is not necessarily a problem
- Deblurring increases software runtime by multiple magnitudes, greatly over requirement of 15min. to output
    - Runtime can be drastically reduced by isolating regions of images to deblur (based on image cropping when CubeSats are found)

Overall System Software Solution



Post-processing Software Solution



UML Software Class Diagram

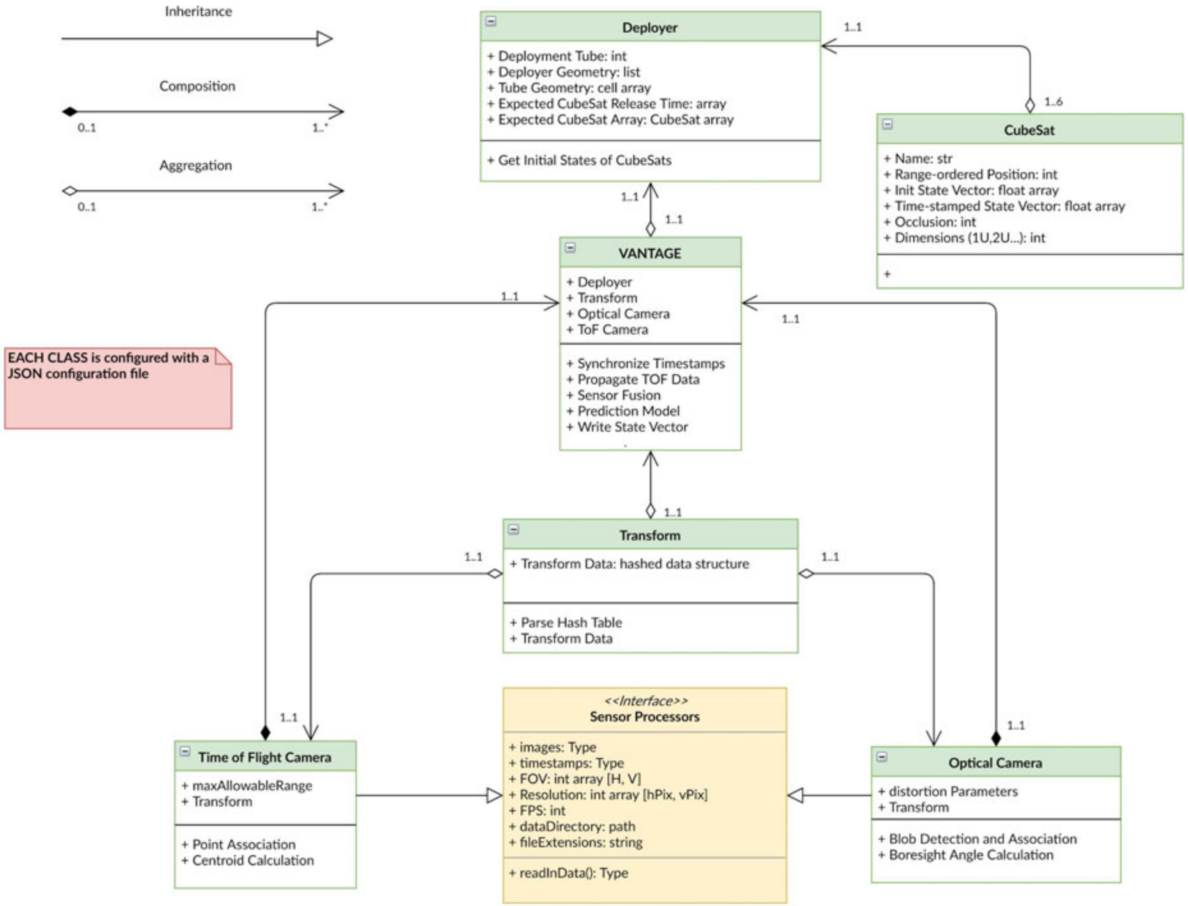
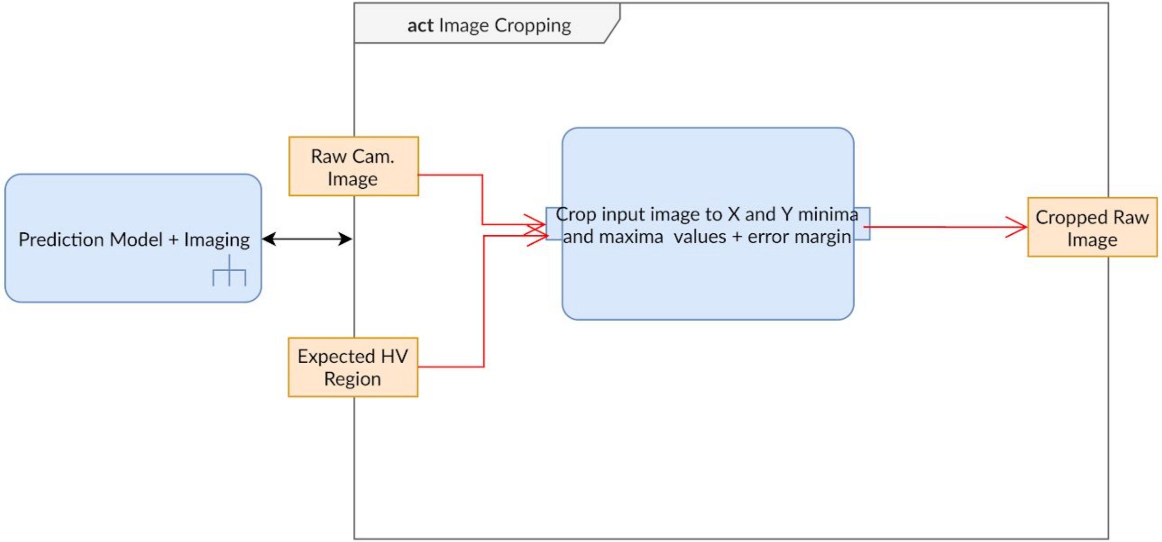
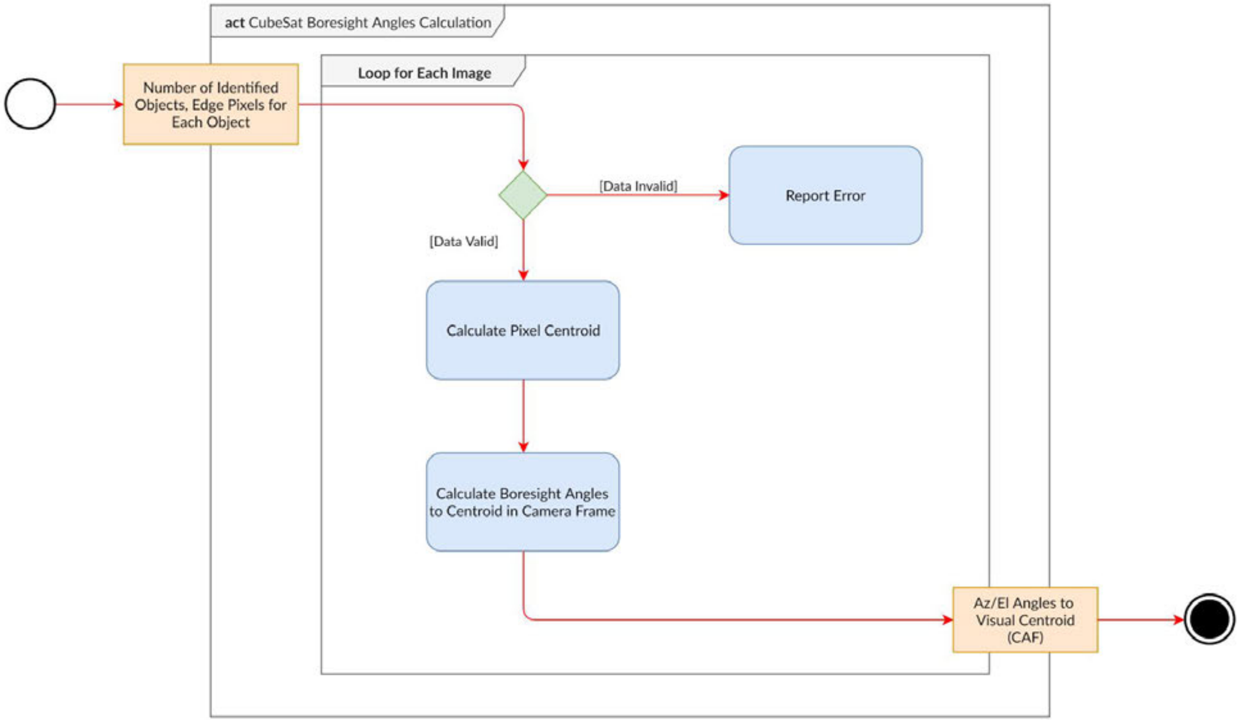


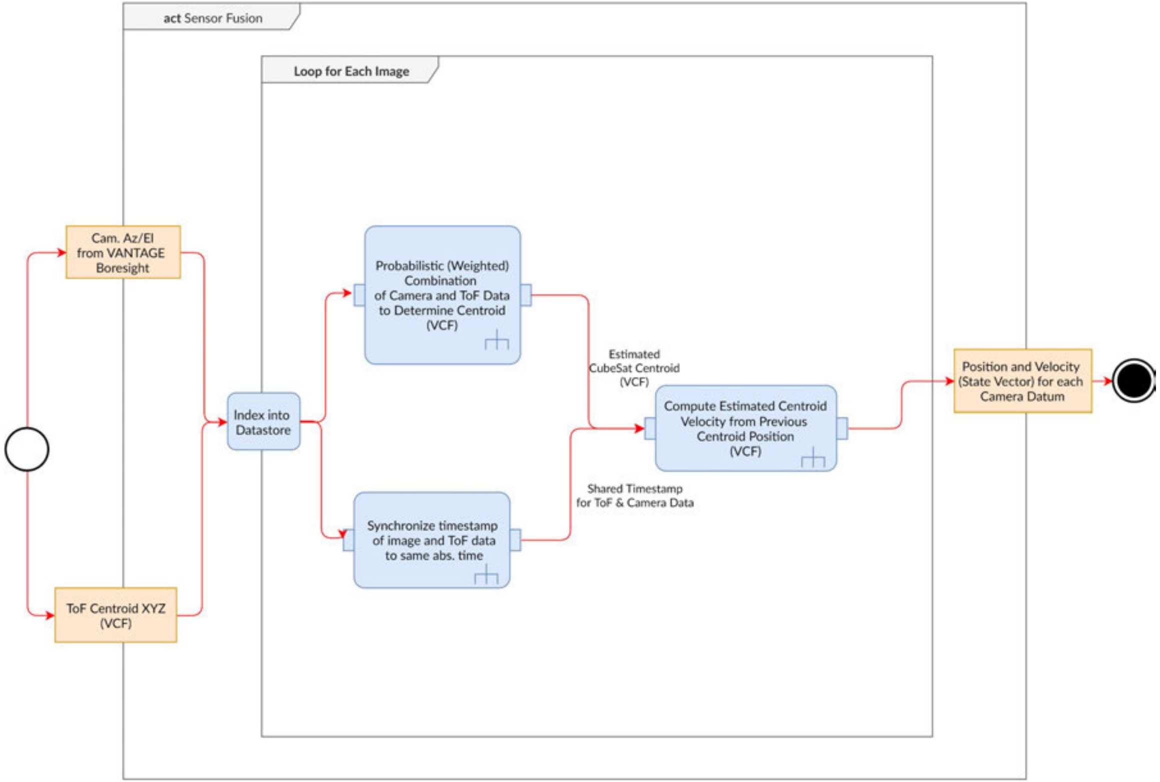
Image Cropping



Boresight Angles Calculations



Sensor Fusion



Prediction Model

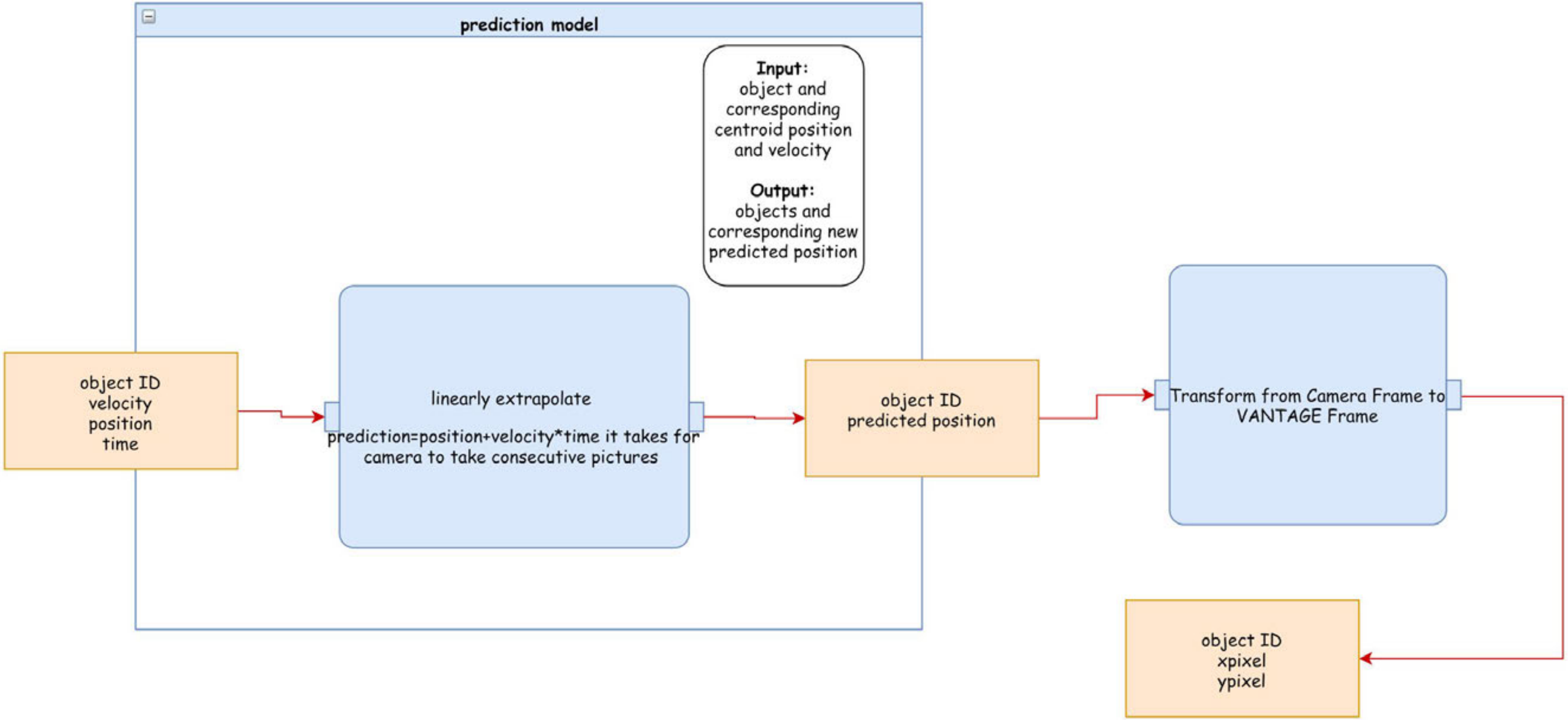
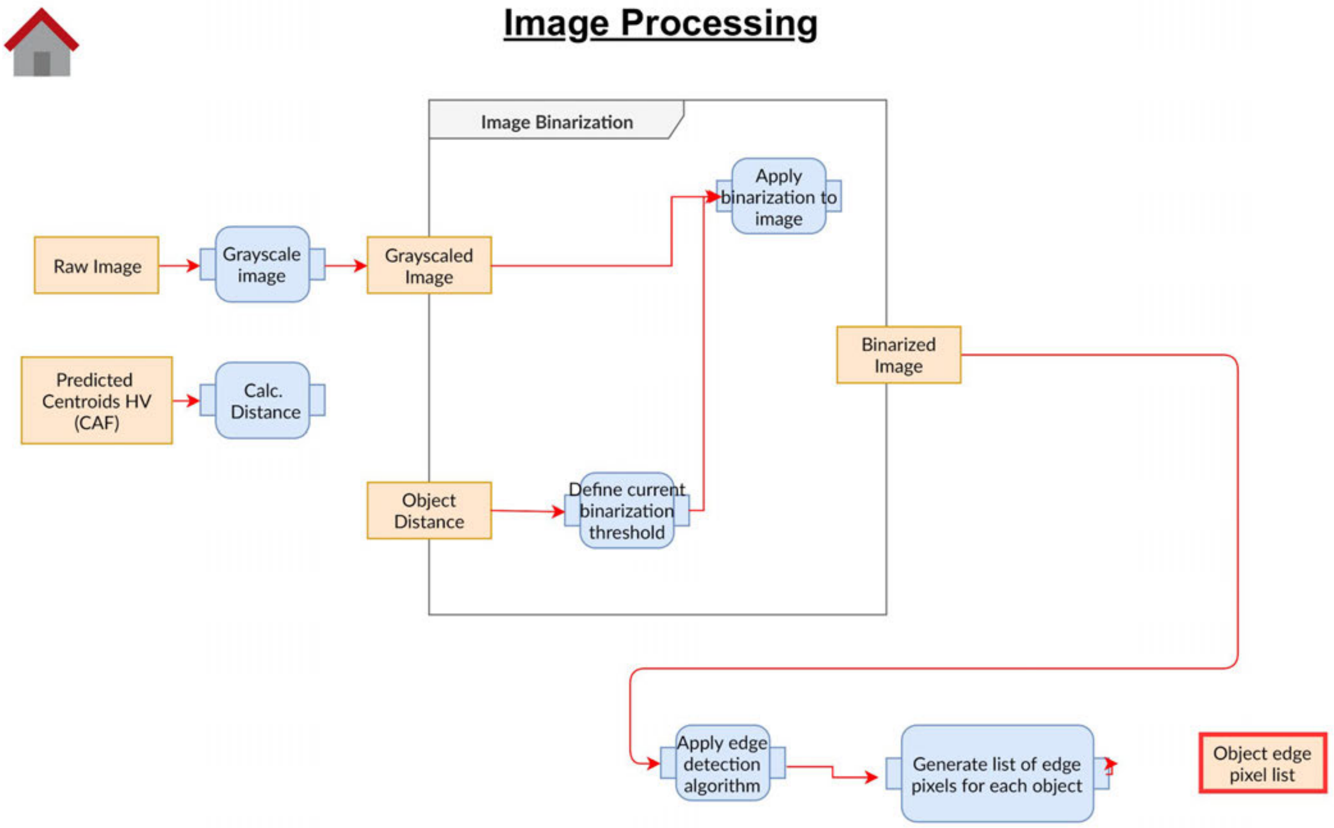


Image Processing



Lens Distortion

Most analysis up to this point has assumed a pinhole projection model for the camera.

However, the lens will impart some distortion that needs to be corrected in order to make accurate measurements. The primary distortion will be radially symmetric and can be estimated by a n-order polynomial in terms of r (distance from optical center).

$$x_\mathrm{u} = x_\mathrm{d} + (x_\mathrm{d} - x_\mathrm{c})(K_1 r^2 + K_2 r^4 + \cdots)$$

$$y_\mathrm{u} = y_\mathrm{d} + (y_\mathrm{d} - y_\mathrm{c})(K_1 r^2 + K_2 r^4 + \cdots)$$

There may also be some tangential distortion (dependence on x or y)
Both of these effects can be mitigated by measuring this distortion and removing it in software.

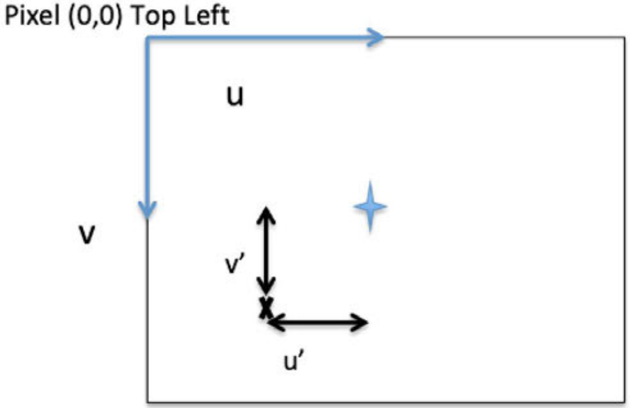
Distortion Removal

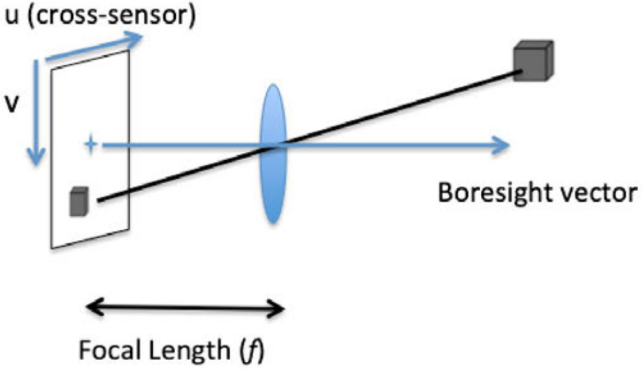
There are useful MATLAB functions that can help to estimate distortion characteristics of a camera.

Basic process:

- Take several images of a checkerboard pattern.
- Use MATLAB Function EstimateCameraParameters
  - Estimates tangential and radial distortion parameters
  - Measures pixel location of optical center
  - Estimates focal length (reality check, should be close to that of our lens)
  - Produces object with all of this information
- Given undistorted Centroid Locations, can undistort using MATLAB undistortPoints()
- This will undistort centroids to their location under a pinhole projection.
- We can then calculate the unit vector that points to the centroid.

Camera Unit Vector Calculation

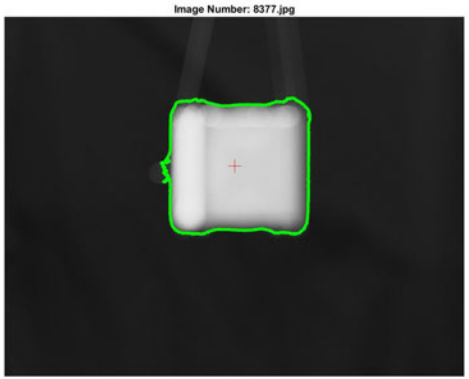


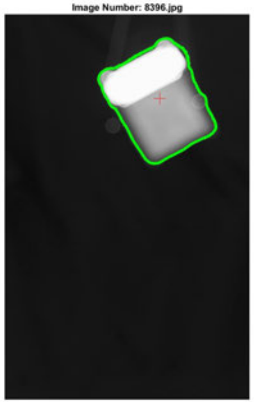


- Centroid determined in pixel coordinates
- Vector to the object defined by coordinate offsets of the centroid (u’ and v’) from the optical center location and the focal length
- Vector = [u’ , v’ , *f*] → Normalize to unit length

	Unit Vector [x,y,z]
Actual Position Unit Vector	[-0.0174 , 0 , 0.9998]
Measured Unit Vector	[-0.0175 , 4e-5 , 0.9998]
Angular difference	**0.0102 degrees**

Full Range Object Recognition



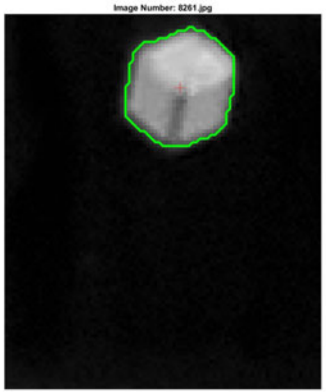


5 m

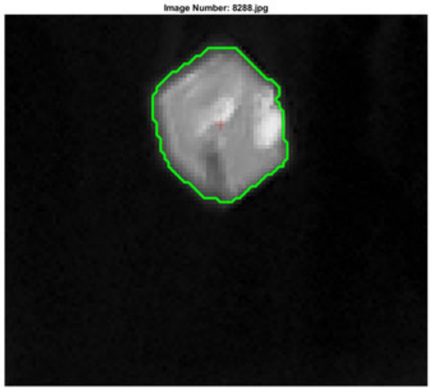
5 m

5 m

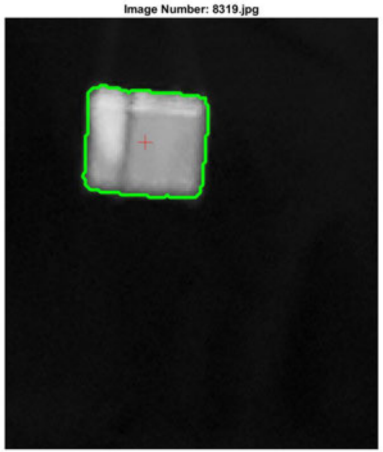
Full Range Object Recognition



70 m



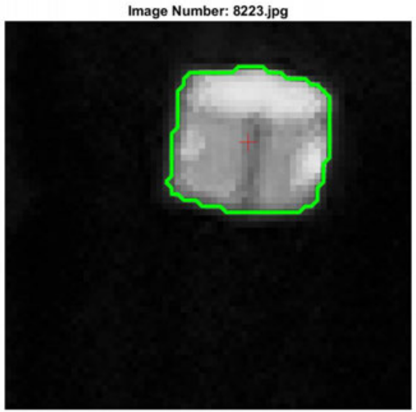
60 m

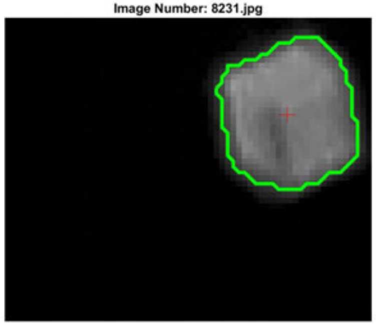


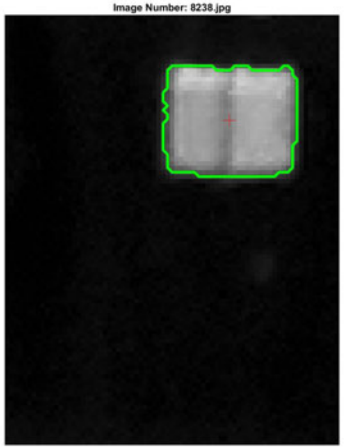
40 m

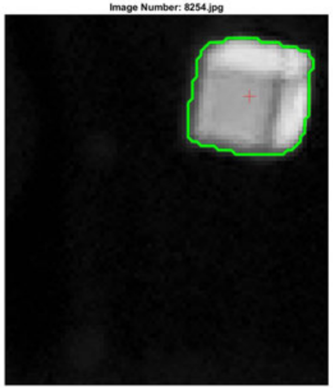
30 m

Full Range Object Recognition









80 m

80 m

70 m

70 m

- Industry standard animation and effects professional software

- We are using free student licenses

- Parametric configuration in **YAML config files**
    - Types of CubeSats
    - Separations, Linear / Angular Velocities
    - Coordinate Systems
    - Sampling Rates, Camera / ToF Params

- Created a **python plugin** using C4D Python API
    - Input python
    - Output .fbx files to input animation, camera, and lighting to Blensor

File Edit Selection Find View Goto Tools Project Preferences Help

Simulation Setup Python Plugin

FOLDERS

- 13 Simulation
  - 1 C4D ORGINfile
  - 2 3D Models
  - 3 C4D Scripts
    - .idea
    - config
      - config_simulation_Josh_CDR (1).yaml
      - config_simulation_Josh_CDR.yaml
      - config_simulation_justin.yaml
      - config_simulation_template.yaml
      - desktop.ini
      - Dylan_partial_noblur.yaml
      - DylansUltimateconfig_simulation_template.yaml
      - dylantruthsimulation.yaml
    - .gitignore
    - __init__.py
    - desktop.ini
    - runSimulation_main.py
  - 4 MISC file
  - 5 Documentation
  - 6_C4D_Simulation_Cases
  - 7_Blensor_Simulation_Cases
  - 8 Modified Blensor
  - 9 Documentation
  - desktop.ini
  - dylan.jpg
  - README.md

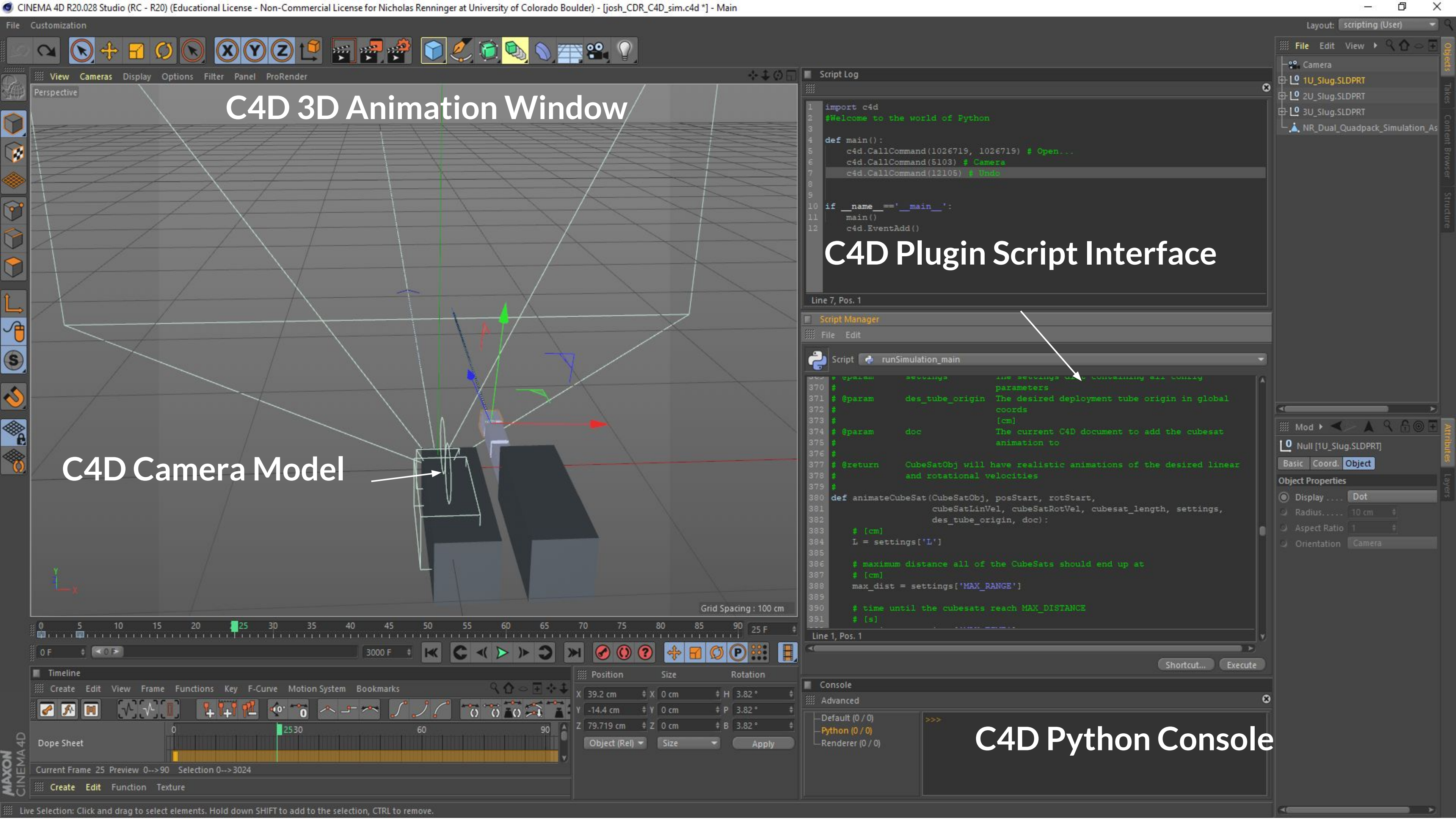
runSimulation_main.py

```python

#
# @brief      Positions and animates the CubeSat object based on the
#             simulation, animation, and geometric definitions given in the
#             config file
#
#             @see getAnimationFrameNumbers and @see getLastPosAndRot for most
#             of the specific animation calculations - animations are applied
#             with the deployer movement constraints in mind
#
# @param      CubeSatObj       The cubesat object to place and animate
# @param      posStart         The start location of the CubeSat's centroid
#                              in global coords.
#                              [cm, cm, cm]
# @param      rotStart         The start rotation of the CubeSat
#                              in global coords.
#                              [rad, rad, rad]
# @param      cubeSatLinVel    The cube sat lin velocity vector to animate
#                              [cm/s, cm/s, cm/s]
# @param      cubeSatRotVel    The cube sat rot velocity vector to animate
#                              [rad/s, rad/s, rad/s]
# @param      cubesat_length   The total cubesat length
#                              [cm]
# @param      settings         The settings dict containing all config
#                              parameters
# @param      des_tube_origin  The desired deployment tube origin in global
#                              coords
#                              [cm]
# @param      doc              The current C4D document to add the cubesat
#                              animation to
#
# @return     CubeSatObj will have realistic animations of the desired linear
#             and rotational velocities
#
def animateCubeSat(CubeSatObj, posStart, rotStart,
                   cubeSatLinVel, cubeSatRotVel, cubesat_length, settings,
                   des_tube_origin, doc):
    # [cm]
    L = settings['L']

    # maximum distance all of the CubeSats should end up at
    # [cm]
    max_dist = settings['MAX_RANGE']

    # time until the cubesats reach MAX_DISTANCE
    # [s]
    max_time = settings['MAX_TIME']

    fps = doc.GetFps()

    # getting the starting and ending frames for all of the animations
    (linVelZStartFrame,
     rotAndLinXYVelStartFrame,
     endFrame) = getAnimationFrameNumbers(L, cubesat_length,
                                          posStart, max_dist,
                                          des_tube_origin,
                                          fps, cubeSatLinVel[2])

```

config_simulation_template.yaml

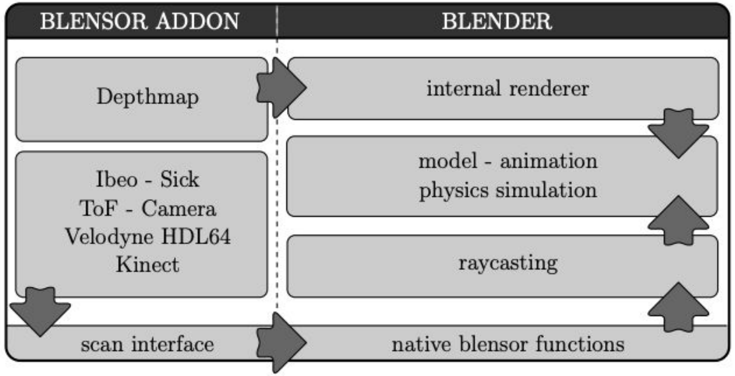
```yaml
# number of frames per second to render the simulation video at
# [frames/sec]
OPTICAL_CAMERA_FPS: 30

# a list of the U sizes and ordering (1U, 2U, 3U) of CubeSats to launch
# the CubeSats are loaded into the deployer tube like a musket
CUBESATS_SIZES:
  # this one goes against the pusher plate (back cubesat)
  - '1U'
  - '1U'
  - '1U'
  - '3U'
  # the above CubeSat one leaves first (front cubesat)

# Select the deployment tube you would like to launch from
DESIRED_DEPLOYMENT_TUBE: 2

# a list of the cartesian CubeSats spacings between each CubeSat in the
# deployment simulation.
#
# If there are N CUBESATS_SIZES, there will be N - 1 CUBESAT_SEPARATIONS
#
# [cm]
CUBESAT_SEPARATIONS:
  - 3
  - 3
  - 3

# a list of the cartesian CubeSats linear velocities for each CubeSat in the
# simulation.
# [v_x, v_y, v_z]
# [cm/s]
CUBESAT_LIN_VELS:
  v_x:
    - 0
    - 0
    - 0
    - 0
  v_y:
    - 0
    - 0
    - 0
    - 0
  v_z:
    - 100
    - 100
    - 100
    - 100

# a list of the cartesian CubeSats rotation velocities for each CubeSat in the
# simulation.
# [omega_x, omega_x, omega_x]
# [rad/s]
CUBESAT_ROT_VELS:
  omega_x:
    - 1.0
    - 1.0
    - 1.0
    - 1.0
```

Simulation YAML Config File


CINEMA 4D R20.028 Studio (RC - R20) (Educational License - Non-Commercial License for Nicholas Renninger at University of Colorado Boulder) - [josh_CDR_C4D_sim.c4d *] - Main
C4D 3D Animation Window
C4D Camera Model
C4D Plugin Script Interface
C4D Python Console
Script Log
import c4d
#Welcome to the world of Python
def main():
c4d.CallCommand(1026719, 1026719) # Open...
c4d.CallCommand(5103) # Camera
c4d.CallCommand(12105) # Undo
if __name__=='__main__':
main()
c4d.EventAdd()
Script Manager
runSimulation_main
def animateCubeSat(CubeSatObj, posStart, rotStart,
cubeSatLinVel, cubeSatRotVel, cubesat_length, settings,
des_tube_origin, doc):
L = settings['L']
max_dist = settings['MAX_RANGE']
Console
Camera
1U_Slug.SLDPRT
2U_Slug.SLDPRT
3U_Slug.SLDPRT
NR_Dual_Quadpack_Simulation_As
Grid Spacing : 100 cm
Timeline
Dope Sheet
Live Selection: Click and drag to select elements. Hold down SHIFT to add to the selection, CTRL to remove.

Blensor

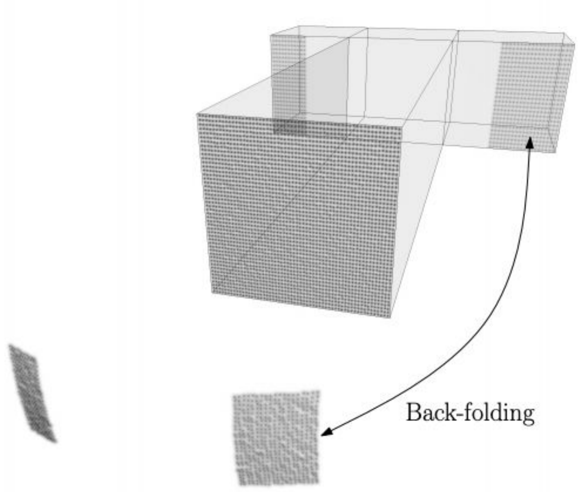
- An add-on running in Blender GUI
- A thesis for a PHD. Michael Gschwandtner "*Support Framework For Obstacle Detection on Autonomous Trains*" University of Salzburg
- The main purpose of Blensor is to simulate a 3-D ToF sensor and test the sensor for autonomous train. It will use all the model built in blender with ray-tracing techniques and physics models to simulate a ToF sensor
- The sensor simulation interface is a part of the blender GUI. It can be used simply use for adjusting all the different parameter for the sensor (such as reflection & noise)

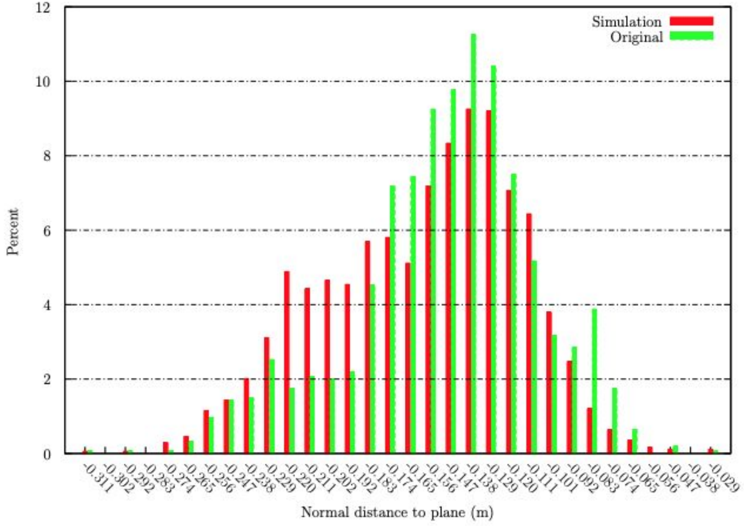


Blensor Validation Test

- It use physics model to capture all of the ToF's sensor characteristics

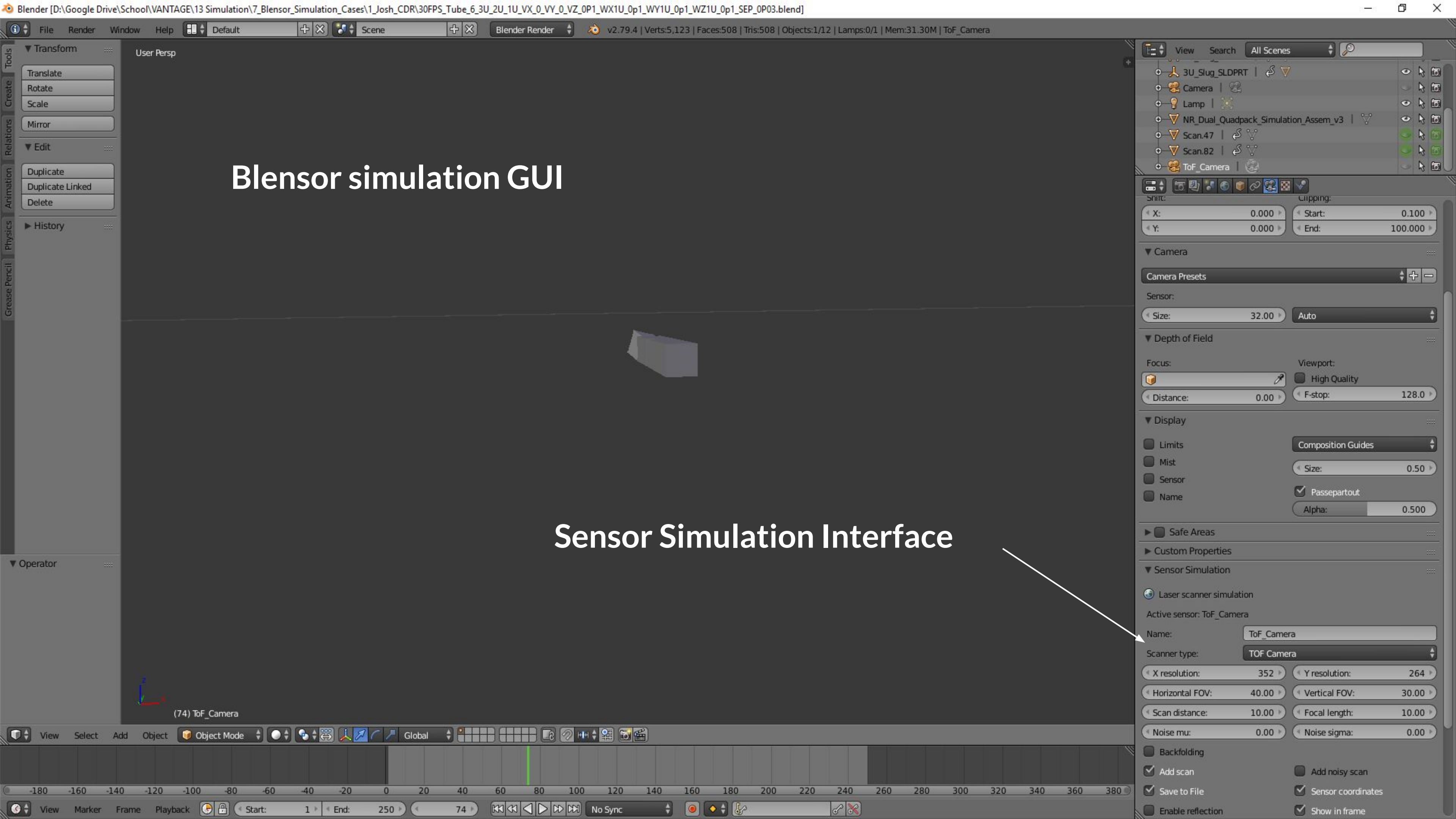
Such as below the back-folding effect from ToF sensor:



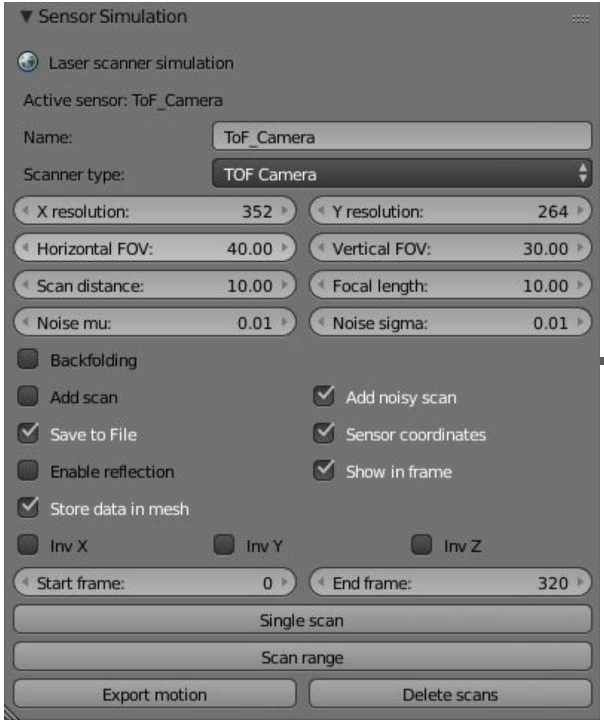


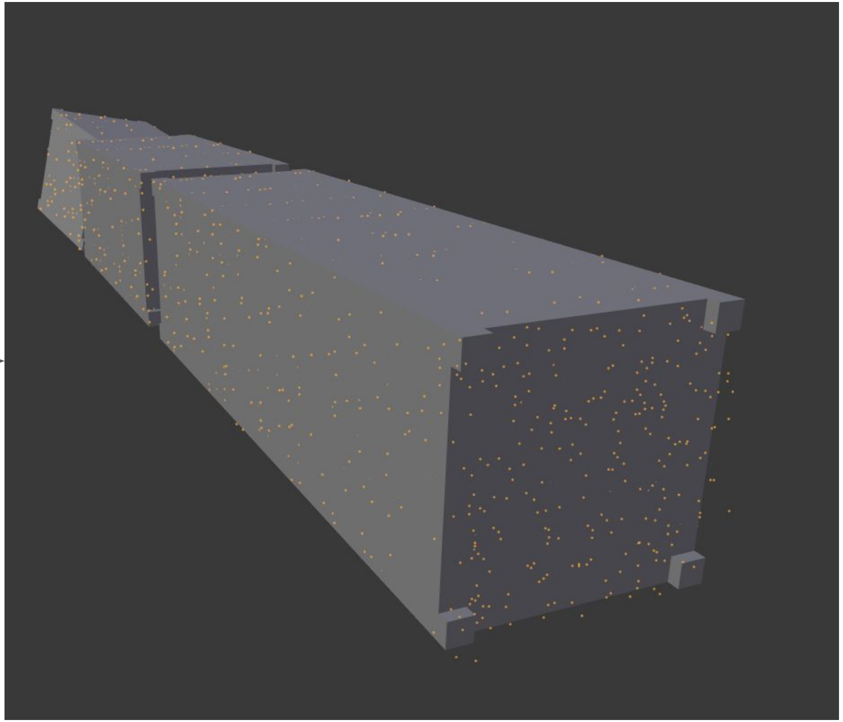
Comparison of normal distances from a real and simulated scan to a wall

PHD. Michael Gschwandtner , "Support Framework For Obstacle Detection on Autonomous Trains", University of Salzburg


Blensor simulation GUI
Sensor Simulation Interface
Blender [D:\Google Drive\School\VANTAGE\13 Simulation\7_Blensor_Simulation_Cases\1_Josh_CDR\30FPS_Tube_6_3U_2U_1U_VX_0_VY_0_VZ_0P1_WX1U_0p1_WY1U_0p1_WZ1U_0p1_SEP_0P03.blend]
v2.79.4 | Verts:5,123 | Faces:508 | Tris:508 | Objects:1/12 | Lamps:0/1 | Mem:31.30M | ToF_Camera
User Persp
(74) ToF_Camera
3U_Slug_SLDPRT
Camera
Lamp
NR_Dual_Quadpack_Simulation_Assem_v3
Scan.47
Scan.82
ToF_Camera
Sensor Simulation
Laser scanner simulation
Active sensor: ToF_Camera
Name: ToF_Camera
Scanner type: TOF Camera
X resolution: 352
Y resolution: 264
Horizontal FOV: 40.00
Vertical FOV: 30.00
Scan distance: 10.00
Focal length: 10.00
Noise mu: 0.00
Noise sigma: 0.00
Backfolding
Add scan
Add noisy scan
Save to File
Sensor coordinates
Enable reflection
Show in frame

Blensor Simulation Test



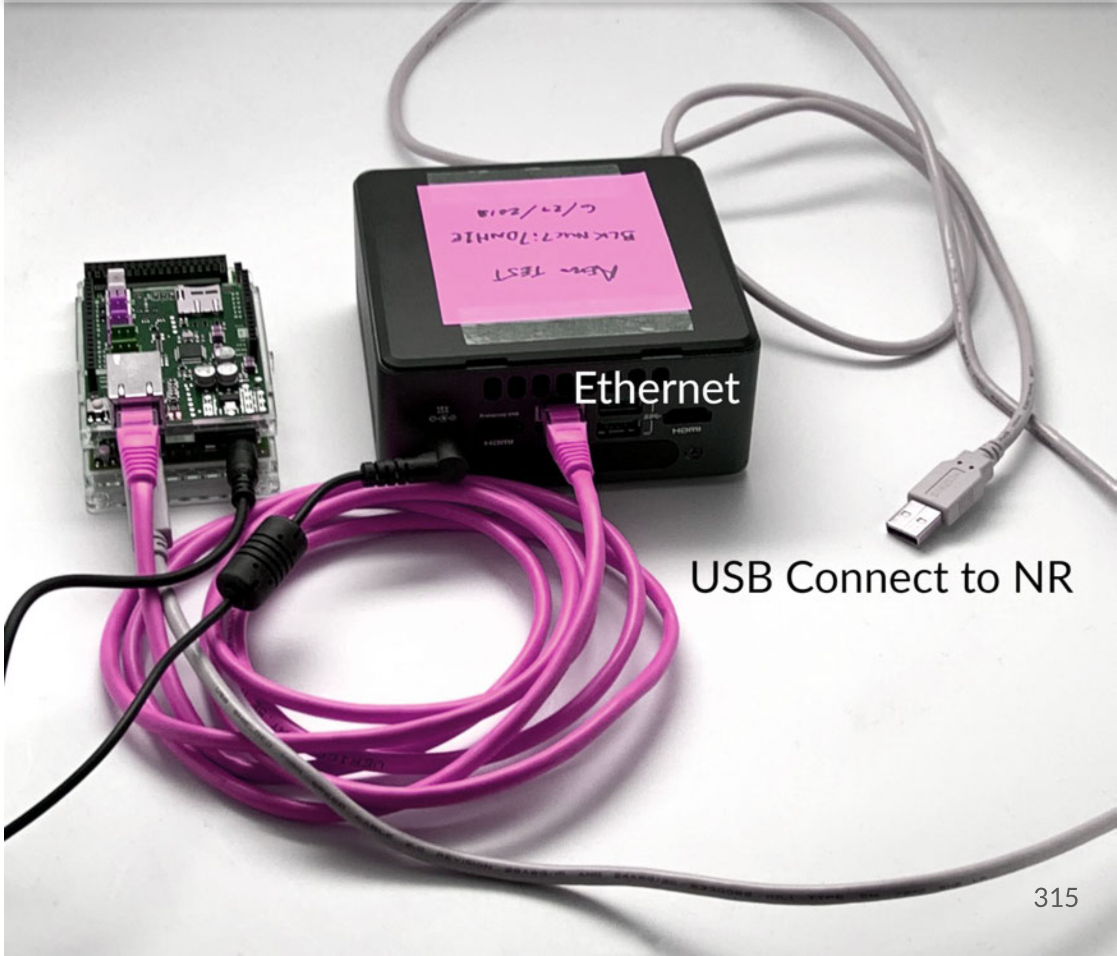


Electronics Backup

All COTS Hardware

DCDC 120V-24V

DCDC
24V-19V/9V

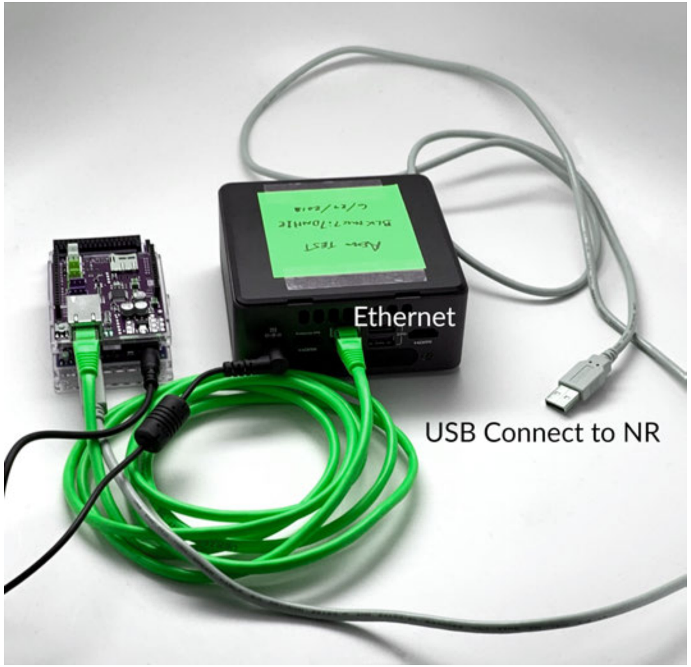


Electronic Design Requirements

Req. Label	Summary	Satisfied
DR. 2.1	The electronics subsystem shall interface with the PC which simulates the NanoRacks use-case system via a USB2.0 Port for all data communication needs.	Yes
DR. 3.1	The system shall operate with up to 120 VDC with a ripple voltage of 3Vpp and less than 5 A, which simulates the power available from the NanoRacks use-case system.	Yes
DR. 3.2	The system shall draw less than 520 Watts.	Yes
DR. 3.3	The electronics subsystem shall enter a low power mode when not performing any operations (i.e. before a final test has been started, after a final test has been completed and all post-processing and communications have completed).	Yes
DR. 8.1	The electronics subsystem shall transmit all relative position and velocity vector estimates and uncertainties, as well as mock CubeSat deployment images back to the PC which simulates the NanoRacks use-case system within 15 minutes of final mock CubeSat deployment.	Yes
DR. 8.2	The system shall store all images, sensor data, and estimates within an onboard data storage device.	Yes

Avionics - Communication (DR 2.1)

- *Vantage can communicating with the Nanoracks use-case system via Arduino USB serial port.*



Req.	Summary
DR 2.1	The electronics subsystem shall interface with the PC which simulates the NanoRacks use-case system via a USB2.0 Port for all data communication needs.

Avionics-Power Supply (DR 3.1)

Feasible? Yes:

- The VANTAGE system needs to step down from 120 VDC to 24VDC and from 120VDC to 19VDC

- 120V to 24V DC DC Converter
  - MEAN WELL USA Inc. DDR120D
    - $63.00
    - 120W max (~40W more power than we expect to draw)

- 24V to 19V DC DC Converter
  - TDK-Lambda Americas Inc. 285-2857-ND
    - $35.00
    - 250W max

Image Credit: DigiKey

Req. Label	Summary
DR.3.1-EL	The system shall operate with up to 120 VDC with a ripple voltage of 3Vpp and less than 5 A, which simulates the power available from the NanoRacks use-case system.

Mean Well DDR-120D

MEAN WELL 120W DIN Rail Type DC-DC Converter **DDR-120 series**

SPECIFICATION

MODEL		DDR-120C-12	DDR-120C-24	DDR-120C-48	DDR-120D-12	DDR-120D-24	DDR-120D-48
OUTPUT	DC VOLTAGE	12V	24V	48V	12V	24V	48V
	RATED CURRENT	10A	5A	2.5A	10A	5A	2.5A
	CURRENT RANGE	0 ~ 10A	0 ~ 5A	0 ~ 2.5A	0 ~ 10A	0 ~ 5A	0 ~ 2.5A
	RATED POWER	120W	120W	120W	120W	120W	120W
	PEAK CURRENT	15A	7.5A	3.75A	15A	7.5A	3.75A
	PEAK POWER Note.5	180W (3sec.)					
	RIPPLE & NOISE (max.) Note.2	50mVp-p	50mVp-p	50mVp-p	50mVp-p	50mVp-p	50mVp-p
	VOLTAGE ADJ. RANGE	9 ~ 14V	24 ~ 28V	48 ~ 56V	9 ~ 14V	24 ~ 28V	48 ~ 56V
	VOLTAGE TOLERANCE Note.3	±1.0%	±1.0%	±1.0%	±1.0%	±1.0%	±1.0%
	LINE REGULATION	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%
	LOAD REGULATION	±1.0%	±1.0%	±1.0%	±1.0%	±1.0%	±1.0%
	SETUP, RISE TIME	500ms, 60ms @48Vdc			500ms, 60ms @110Vdc		
	HOLD UP TIME (Typ.)	comply with S1 level (6ms) @ full load, S2 level (10ms) @ 60% load			comply with S2 level (10ms) @ full load		
INPUT	VOLTAGE RANGE Note.4	33.6 ~ 67.2Vdc	33.6 ~ 67.2Vdc	33.6 ~ 67.2Vdc	67.2 ~ 154Vdc	67.2 ~ 154Vdc	67.2 ~ 154Vdc
	EFFICIENCY (Typ.)	89.5%	91%	92%	89.5%	91%	91.5%
	DC CURRENT (Typ.)	2.8A @48Vdc			1.3A @110Vdc		
	INRUSH CURRENT (Typ.)	5A @48Vdc			5A @110Vdc		
PROTECTION	OVERLOAD	Normally works within 150% rated output power for more than 3 seconds and then constant current protection 105~135% rated output power with auto-recovery					
	OVER VOLTAGE	14.4 ~ 16.8V	28.8 ~ 33.6V	57.6 ~ 67.2V	14.4 ~ 16.8V	28.8 ~ 33.6V	57.6 ~ 67.2V
		Protection type : Shut down o/p voltage, re-power on to recover					

TDK-Lambda I6AP

Electrical Data:

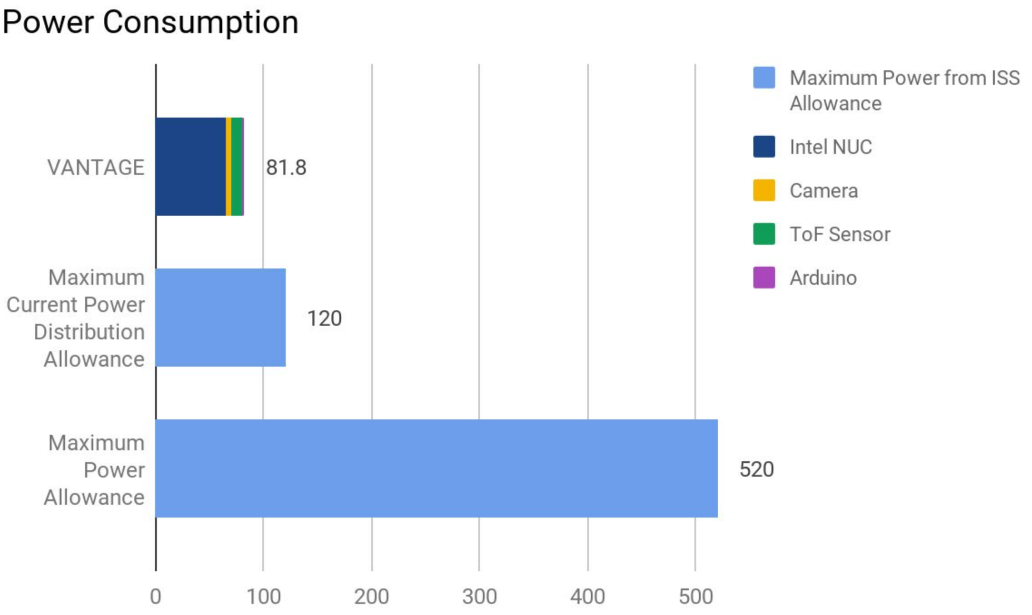
Characteristic	Min	Typ	Max	Unit	Notes & Conditions
Output Voltage Initial Setpoint	-2	-	+2	%	Vo=3.3Vsetting, Vin=Vin,nom; Io=Io,min; Tc = 25˚C
Output Voltage Tolerance	-4	-	+4	%	Over all rated input voltage, load, and temperature conditions to end of life
Efficiency Vo = 3.3V Vo = 5V Vo = 8V	--- --- ---	92.5 94.5 96	--- --- ---	% % %	Vin=12V; Io=Io,max; Tc=25˚C
Efficiency Vo = 5V Vo = 12V Vo = 15V Vo = 20V	--- --- --- ---	92.5 96.5 97 98	--- --- --- ---	% % % %	Vin=24V; Io=Io,max; Tc=25˚C
Line Regulation	---	0.3	---	%	Vin=Vin,min to Vin,max
Load Regulation	---	1	---	%	Io=Io,min to Io,max
Output Current	0	---	14	A	Observe maximum power limit
Output Current Limiting Threshold	---	22	---	A	Vo = 0.9*Vo,nom, Tc<Tc,max
Short Circuit Current	---	0.5	---	A	Vo = 0.25V, Tc = 25˚C
Output Ripple and Noise Voltage	---	20	---	mVpp	Measured across one 0.1 uF ceramic capacitor and one 22uF ceramic capacitor – see input/output ripple measurement figure; BW = 20MHz.
Output Voltage Adjustment Range	3.3	---	24	V	
Output Voltage Sense Range	---	---	5	%	
Dynamic Response: Recovery Time Transient Voltage	 --- ---	 50 500	 --- ---	 uS mV	di/dt =1A/uS, Vin=Vin,nom; Vo=12V, load step from 25% to 75% of Io,max
Switching Frequency	---	400	---	kHz	Fixed
External Load Capacitance	0	---	2000*	uF	
Vref	---	0.6	---	V	Required for trim calculation
F	---	36500	---	Ω	Required for trim calculation
G	---	511	---	Ω	Required for trim calculation

*Please contact TDK - Lambda Americas for technical support for very low esr capacitor banks or if higher capacitance is required

Avionics - Power Consumption (DR 3.2)

Feasible? Yes

- *VANTAGE power usage below maximum power allowance*
- *Power (Max) Break Down*
    - *NUC - 65W*
    - *Camera - 5W*
    - *ToF Sensor - 10W*
    - *Arduino Mega with Shield - 1.8 W*
    - *Total - 81.8 W*



Req.	Summary
DR 3.2	The system shall draw less than 520 Watts.

Electronic Low Power mode (DR3.3)

- During the Avionics low power mode, only the Arduino Mega will be online.
- When the Nanorack's use-case system sends the metadata file through the USB2.0 connection, Arduino will send a Wake-on-Lan package through the Ethernet connection. (DHCP)
- The Wake-on-Lan functionality is based on the Linux Wake-On-Lan script. It works by using the PC IP and MAC address to target the NUC and wake it up.

Req. Label	Summary
DR.3.3-EL	The electronics subsystem shall enter a low power mode when not performing any operations (i.e. before a final test has been started, after a final test has been completed and all post-processing and communications have completed).

Data Processing Time Calculations (DR 8.1)

- A data file, following the NanoRack's format, is input through USB 3.0 to the NUC. Slowest transfer speed: 220.1MB/S
  - Import from ToF
    - The total ToF data worse case(0.5 /s deployment) will have 600 frames of data and a single file size of 2.4 MB. Transferring this on USB3.0 will take 6.54 Sec.
  - Import from Camera
    - The total Camera worst case will have 400 frames and a single file size of 6.41 MB (8-bits Single Channel 3088x2076 footage). Transferring this on USB3.0 will take 11.65 Sec.
  - The following programs were run on the NUC:
    - ToF Centroiding - 0.2 sec per point cloud
    - Image Processing - 0.26 sec per image
    - Camera Distortion - 0.132 sec per image
    - Sensor Fusion - 1.68e-4 sec per image
  - Output to NR with 76800 Baud rate serial USB2.0 output. We are looking at a 0.2% bit error.

Req.	Summary	Addressed in Slide(s)
DR 8.1	VANTAGE shall have ability to store and processing large amount data in 15 Min	

Arduino USB2.0 Output Bit Error

16 Mhz		
Baud	**UBRR**	**% of error**
300	3332	0.0
600	1666	0.0
1200	832	0.0
2400	416	0.1
4800	207	0.2
9600	103	0.2
14400	68	0.6
19200	51	0.2
28800	34	0.8
38400	25	0.2
57600	16	2.1
76800	12	0.2
115200	8	3.7

- AVR Baud Rate Table
- $UBPR = \frac{fosc}{16BAUD} - 1$
- We will use a Baud Rate of 76800 for the USB communication with NR
- 9.6 Kb/s Uplink Speed

Data Storage Calculations (DR 8.2)

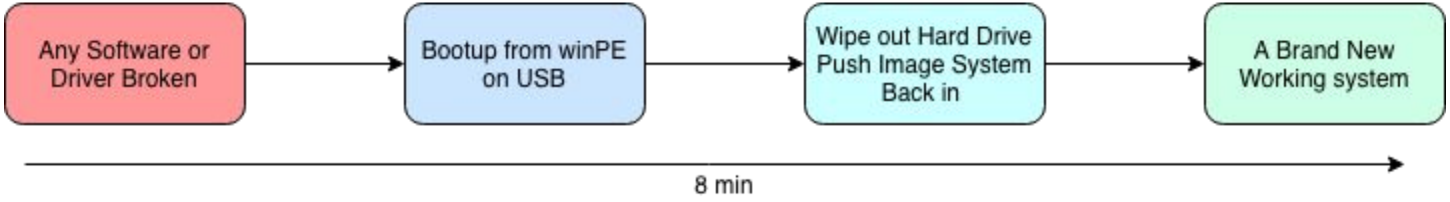
	Normal Size	Number	Total
TOF data	2.4 MB per frame	600 frames	1440 MB
Camera Data	6.41 MB per frame	400 frames	2564 MB
Windows Size	20GB	1	20480 MB
Matlab	15GB	1	15360 MB
Total			39.94 GB

Req.	Summary
DR 8.2	The system shall store all images, sensor data, and estimates within an onboard data storage device.

Fast Recovery For Testing

To eliminate VANTAGE avionics driver issues and operating system errors, the following will be used:

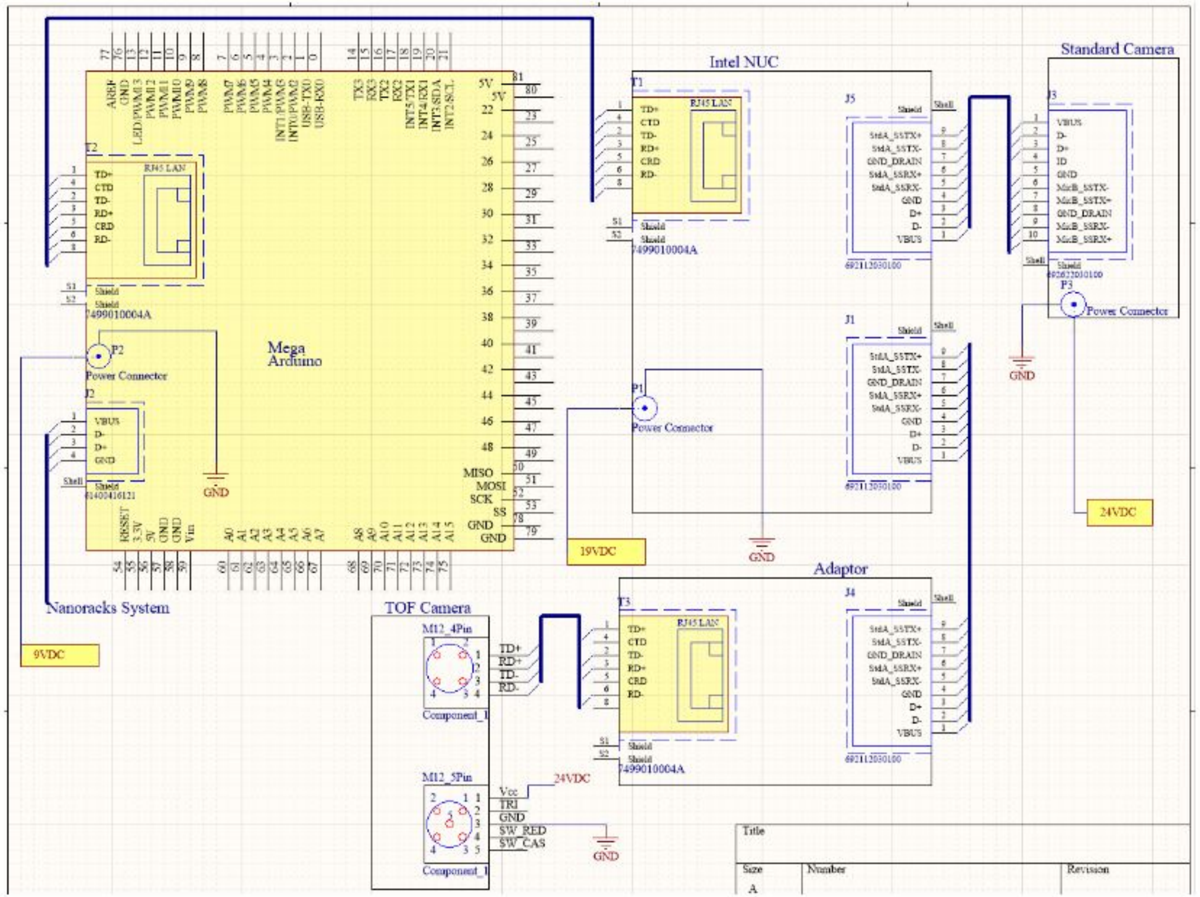
- All VANTAGE drivers and software will be clean installed and the system will be imaged.
- WinPE(Windows Preinstallation Environment) will be used in case things need to be recovered or windows needs to be repaired.



Avionics -Parts Break Down

Electronic Parts	
Intel NUC	1
USB To Ethernet Converter	1
DCDC: Mean Well 120D-24	1
DCDC: TDK-Lambda Americas I6AP Series	2
Arduino Mega 2560	1
Arduino Ethernet Shield R3	1

Wiring Diagram



Power Distribution - Test Plan

- The XFR 300-4 power supply (provided by Trudy) will be used to simulate the 120V NanoRacks power system.
- The Keysight N3301A load tester (provided by Tim May) will be used to test voltage variation in this supply. This system can take a 0-600W load.